

# DOUBLED TROUBLE

## MORE MIDWESTERN EXTREME STORMS



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## About RMCO

The Rocky Mountain Climate Organization (RMCO) works to reduce climate disruption and its impacts. We do this in part by spreading the word about what a disrupted climate can do to us and what we can do about it. Visit [www.rockymountainclimate.org](http://www.rockymountainclimate.org) to learn more about our work.

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# EXECUTIVE SUMMARY

Rare extreme-weather events are becoming more common, and scientists link those increases to the effects of human disruption of the climate. Heavy precipitation is one form of extreme weather that has increased around the world, with that increase tied to human causes. Big storms can mean big floods, and the largest of storms are coming much more often in the Midwest.

Based on a new analysis of a half century of precipitation records in the Midwest, this report documents how much heavy precipitation has increased in the region, shedding new light on the major flooding of recent years in the Midwest.

## Analysis of Midwestern Extreme Storms

Since 1961, the Midwest has had an increasing number of large storms. The largest of storms, those of three inches or more of precipitation in a single day, increased the most, with their annual frequency having more than doubled over the 51 years. The frequencies of all large storms, especially the largest,

jumped the most in recent years.

These are the central conclusions of a new analysis by the Rocky Mountain Climate Organization (RMCO) of precipitation in the eight midwestern states of Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin. The data are from 218 weather stations in the U.S. Historical Climatology Network (USHCN), the nation's most reliable weather stations. The RMCO analysis covers four more years than previous studies, and that new data helps make it clear how much precipitation patterns in the Midwest have changed in recent times.

The RMCO analysis shows the changes in midwestern storms of different sizes, first by comparing their average frequencies by decade to the frequencies in 1961-1990. As Figure ES-1 below shows, with each step up in the size of storms comprising a category, the increase in their frequency became greater. As the figure also shows, the rates of increase for all large storms accelerated over time, with the last analyzed decade, 2001-2010, having the greatest jumps. For the largest storms, called

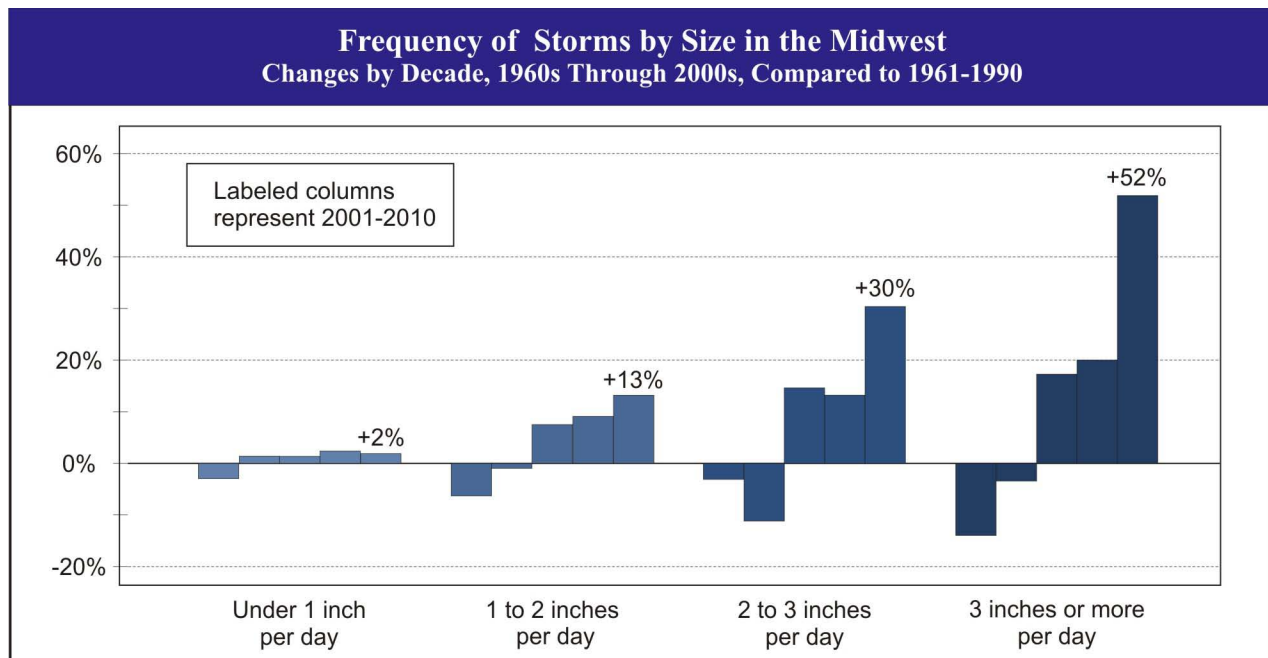


Figure ES-1. Changes by decade in the annual frequencies per station of storms of different sizes, compared to 1961-1990. Storms are grouped by days with less than 1 inch of precipitation, at least 1 inch but less than 2 inches, at least 2 but less than 3 inches, and 3 inches or more. In each group, the columns from left to right represent 1961-1970, 1971-1980, 1981-1990, 1991-2000, and 2001-2010.



extreme storms in this report, in 2001-2010 there were 52% more storms per year than in the baseline period.

Another way to show the changes in storm frequencies is statistical trends in their annual frequencies between 1961 and 2011. The frequency of three-inches-plus storms increased by 103% over these 51 years. For storms of at least two inches but less than three inches in a day, the trend was an 81% increase; for storms of one to two inches, a 34% increase; and for small storms of less than one inch, an 8% increase.

**The RMCO analysis shows very clear patterns. The larger the storms, the more their frequency increased. And the increases have been greatest in recent years.**

The frequency of extreme storms has increased so much in recent years that the first 12 years of this century included seven of the nine top years (since 1961) for the most extreme storms in the Midwest.

With more frequent extreme storms, the average return period between two such storms has become shorter. In 1961-1970, extreme storms averaged once every 3.8 years at an individual location in the Midwest. That is two to four times more frequent than a major hurricane making landfall at a typical location along the U.S. coast from North Carolina to Texas. By 2001-2010, the average return period for midwestern extreme storms at a single location was down to 2.2 years—or four to eight times more frequent than landfalling major hurricanes.

The table below presents key results of the analysis for extreme storms in the Midwest since 1961.

3-Inches-Plus Storms in the Midwest							
	Trend in Annual Values 1961-2011	Average Changes by Decade Compared to 1961-1990					Top 10 Years 1961-2011 and Flooding Disasters(*)
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	
Frequency of 3-Inches-Plus Storms	+103%	-14%	-3%	+17%	+20%	+52%	(1) 2008* (6) 2007* (2) 1993* (7) 2000* (3) 1982* (8) 2004* (4) 2010* (9) 2002* (5) 2011* (10) 1961* 7 in this century
Return Period (in years)	-	3.8	3.4	2.8	2.8	2.2	-
Amount of Precipitation from All 3-Inches-Plus Storms	+108%	-14%	-3%	+17%	+20%	+55%	(1) 2008 (6) 2011 (2) 1993 (7) 2002 (3) 1982 (8) 1986 (4) 2010 (9) 1998 (5) 2007 (10) 2004 6 in this century

Table ES-1. Key results of analysis of days with at least 3 inches of precipitation. Frequency refers to the average number of days per station per year of 3-inches-plus storms. Return period refers to the average length of time between such storms. Precipitation refers to the average amount of precipitation per station per year from all 3-inches-plus storms. Trends for 1961-2011 are in annual values over 51 years. Average changes by decade are the differences between decadal averages and the corresponding values for a baseline period of 1961-1990; for frequency, the changes by decade are as shown in Figure ES-1 for three-inches-plus storms. The top 10 years are the years with the 10 highest values from 1961 through 2011 (and the rank of those years, out of 51 years).

An analysis of the frequencies of extreme storms in the eight midwestern states shows that in each state, as well as in the region, the last analyzed decade (2001-2010) also had the most extreme storms.

The RMCO analysis is generally consistent with previous scientific studies, which also show larger increases in heavy storms than in smaller ones.

## Extreme Storms and Floods

That extreme storms have increased in frequency so much more than all other storms offers an important explanation of the recent years of major flooding in the region.

In isolation, extreme storms can cause flash

flooding. When they occur where soils are already saturated and stream levels are already high, and especially when they occur in rapid succession, extreme storms can cause widespread, sometimes devastating flooding.

Floods are to the Midwest what hurricanes are to coastal areas—the region’s most widely destructive type of regularly occurring natural disaster. Across the United States, flooding is the second most costly type of natural disaster.

The consequences of extreme storms are best illustrated by what happened in the two years that topped the RMCO analysis of frequency of extreme storms in the region: 2008 (in first place by a wide margin) and 1993. As Midwesterners well know, in those two years the region experienced widespread flooding that ranks near the top of natural disasters in the nation. Midwestern floods in 2008 cost \$15.8 billion, and the Great Flood of 1993 caused \$32.8 billion in damages. Since 1980, only seven hurricanes were costlier than the flooding of 2008, and only two—Katrina and Andrew—were costlier than the Great Flood of 1993.

Other years with many extreme storms also had destructive flooding. In 2010, which ranked fourth in regional extreme-storm frequency, Iowa alone had \$1 billion in agricultural losses from extreme storms. In 2011, which ranked fifth, midwestern flooding caused \$2 billion in damages.

That years with many extreme storms also had severe flooding supports the common-sense connection between the two. The RMCO analysis also presents two new forms of evidence correlating extreme storms with floods in the Midwest.

One part of that analysis identifies for the first time the contribution that extreme storms made to the worst of the 2008 floods. RMCO analyzed the areas that received the heaviest precipitation—and had the most flooding—in June 1-15, 2008, the height of that year’s destructive floods. In those areas, 48% of the precipitation came from extreme storms. They occurred in those 15 days at more than 100 times the

historic rate. Without the extremely frequent extreme storms, the flooding would not have been so bad.

RMCO also tallied the incidence of federal disaster declarations based on flooding in high, medium, and low years for frequency of extreme storms. The years with more extreme storms had more flooding disasters.

The evidence connecting extreme storms and disastrous flooding makes it clear that the Midwest is vulnerable to more major flooding if the frequency of extreme storms continues accelerating.

## More Pollution, More Trouble

The increase in extreme storms documented in this report is part of a global increase in heavy precipitation that scientists tell us stems from human disruption of the natural climate. A recent study using climate models and statistical analysis demonstrated that human increases in heat-trapping gases appear to be causing increases in heavy precipitation. Detecting a clear human role in changing extreme precipitation patterns at a smaller geographic scale is much more difficult, and scientists have not yet reported any such conclusions for the Midwest. But the number of dots that can be connected is rising—including that all weather events are now affected by climate change, because they occur in a climate hotter and wetter than it used to be.

**A threshold may already have been crossed, so that major floods in the Midwest perhaps now should no longer be considered purely natural disasters but instead natural/unnatural disasters.**

Scientists also project further increases in heavy precipitation as a result of heat-trapping pollution. The higher the levels of future emission of heat-trapping gases, the greater the changes in heavy precipitation are projected to be. The Midwest is a region where future increases in extreme precipitation are expected to be greater than in many other regions.

## Toward a Better Future

The increased frequency of large storms in the Midwest and the costly flooding that often accompanies them demonstrate the need for action on two fronts. First, actions are needed to prepare for and increase resiliency to extreme storms and floods. Second, we need to reduce emissions of the heat-trapping pollution that is already disrupting our climate, so that further increases in extreme weather and other changes are kept to acceptable levels.



Cedar Rapids, Iowa, 2008.

# 1. INTRODUCTION

Babe and Jeanie Herron were sitting on their deck in Columbus [in Indiana] eating sandwiches and watching the storm. They were getting used to the constant sound of the rain...“I heard this lady scream, and I jumped off the porch to see if I could help,” Babe says. “That’s when I saw the water.”

Even with all that rain, Babe wasn’t expecting the rush of water. He’d lived on this street all his life...In all that time, Babe never saw water invade the street like it did on June 7, 2008. It looked like a scene out of a movie, a wave from the nearby creek rolling in like it belonged to the ocean.

“It came across the backyard and then it was in the house,” Jeanie says. “We were both in shock, thinking, ‘This cannot be happening.’”

Jeanie ran inside and gathered an armful of clothes, pictures and their medicine. She saw the water pushing up the carpet and coming out of cracks in the floor and vents.

Extreme weather has become more common in recent decades. This report documents the change in extreme weather most important to the Midwest: an increase in the frequency of heavy storms.

Babe grabbed some bricks and set them on the ground right by his house, hoping this shield would keep the basement dry. It didn’t work.

That’s when he knew the water had them beat. “I yelled to a neighbor, ‘You better get out of your house because those walls could collapse.’”

He walked to the corner, where the ground was higher and Jeanie and others stood watching the water take control...

The scene was surreal, and it was playing out over and over in central and southern Indiana that day.

Indiana Association of United Ways<sup>1</sup>



Columbus, Indiana, 2008.



What Babe and Jeanie Herron faced in June 2008, along with millions of others across the Midwest, was flooding caused by extreme storms. (For more on the particular storm they experienced, see page 22.)

Rare extreme-weather events are becoming more common, according to many sources including a congressionally mandated national assessment of climate change impacts in the United States, prepared by the interagency U.S. Global Change Research Program and published in 2009.<sup>2</sup> Increasingly, scientists are attributing the upturns in different types of extreme events to the effects of human disruption of the climate.<sup>3</sup> Heavy precipitation is one of the forms of extreme weather that has increased—more so in the Midwest than in most of the country—and has been linked to human causes (see pages 18-19). This warrants concern in the Midwest, which is naturally susceptible to major flooding, the region's most destructive form of regularly occurring natural disaster.<sup>4</sup>

This report takes a close look at the changing pattern over the past half century of heavy precipitation in the Midwest—defined here as the states of Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin. The report presents the results of a new analysis showing the extent to which extreme storms have become more frequent over the past 51 years in the region and in each of those eight states.

The increase in heavy storms in the Midwest documented here is but one part of the larger story of more extreme weather in the United States.<sup>5</sup> Since 1980, according to the federal government, there have been 110 weather/climate disasters in the United States with \$1 billion or more (in 2011 dollars) in damages—and 64 of them were in the first 11 years of this century.<sup>6</sup> In 2011, there were a record-

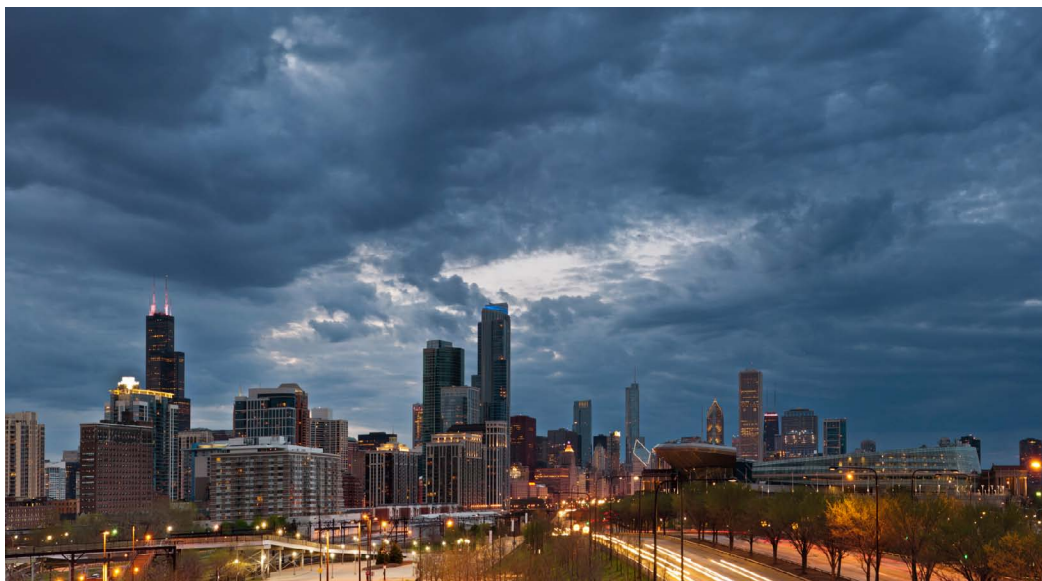
breaking 14 billion-dollar disasters, more than in the entire decade of the 1980s.<sup>7</sup>

The Midwest has certainly had more than its fair share of extreme weather in recent years, from devastating tornadoes to deadly wind storms. But the most important increase in extreme weather in the region is what is reported here: The heaviest of storms have become much more frequent in the Midwest in recent years. The consequences can be more devastating floods, which in the United States are second only to heat waves as the most deadly type of extreme weather and second only to hurricanes as the most costly type of natural disaster.<sup>8</sup> The Midwest has been hit hard in recent years by floods, with those of 2008 and 2011 having caused billions of dollars in damages.

Section 2 of this report presents the results of the new analysis showing a sharp increase in extreme storms in the Midwest since 1961. Section 3 presents data linking extreme storms to flooding, showing why it matters so much that extreme storms are becoming more frequent. Section 4 puts the increase in extreme storms in the broader context of human alteration of the climate. Section 5 recommends actions for preparing for more heavy storms and reducing future climate change. An Appendix details the sources and methodologies for the new analysis reported here.

**“Changes in these kinds of extreme weather and climate events are among the most serious challenges to our nation in coping with a changing climate.”**

U.S. Global Change Research Program<sup>9</sup>



Chicago.

© istockphoto.com/Rudy Balasko

## 2. ANALYSIS OF MIDWESTERN EXTREME STORMS

Big storms can mean big floods, and the largest of storms are coming much more often in the Midwest. For storms of three inches or more of precipitation in a single day, their annual frequency has more than doubled in the last half century, having increased at a statistical rate of 103% between 1961 and 2011. Especially for those storms but also for all large storms, the annual frequencies increased most sharply in recent years.

These are the central conclusions of a new analysis by the Rocky Mountain Climate Organization of daily precipitation records for the Midwest—defined as Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin. The data are from 218 weather stations in the U.S. Historical Climatology Network (USHCN), a national network of high-quality weather stations designed to track long-term climate trends, covering the 51 years from 1961 through 2011. Data through 2010 have been subjected to the USHCN's quality controls to identify possible errors; data from 2011, included in some of the analysis, are preliminary and have not undergone quality controls. (For details of the sources and methodology used in the analysis, see the Appendix on pages 32-35.)

This report apparently is the first to present an analysis of such recent data. With the preliminary 2011 data, this analysis covers four more years than other published studies known to the authors of this report.<sup>10</sup> The additional data from those recent years

Large storms became more frequent in the Midwest from 1961 to 2011, with the greatest increase among the largest storms. The annual rate of extreme storms, those with three inches or more of precipitation in a single day, increased by 103% over those 51 years.

Recent years had the sharpest jump in extreme storms. Of the top nine years for annual frequency of extreme storms, seven are among the first 12 years of this century.

help make it clear how much precipitation patterns in the Midwest have changed in recent times—part of a global trend scientists attribute to human-caused climate change (see Section 4).

### OVERALL PRECIPITATION

Shown in Table 1 below are trends in overall precipitation in the Midwest, including both rainfall and snowfall (measured as inches of water the snow

Overall Precipitation in the Midwest						
	Trend in Annual Values 1961-2011	Average Changes by Decade Compared to 1961-1990				
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010
Total amount of precipitation	+23%	-4%	0%	+5%	+6%	+9%
Frequency of days with precipitation	+10%	-3%	+1%	+2%	+3%	+3%
Amount of precipitation per day with precipitation	+12%	0%	-1%	+3%	+4%	+7%

Table 1. Underlying data are averages per station per year. Trends are for the 51-year period. See the Appendix for details on sources and methodology.

comprises). The annual amount of total precipitation in the Midwest increased at a rate of 23% between 1961 and 2011, reflecting both an increasing frequency of days with precipitation and an increasing average amount of precipitation falling on those days. These three trends are statistically significant, with at least a 95% confidence level (see pages 34-35).

In Table 1, as in others in this report, the preliminary 2011 data are used to show trends for the period 1961 through 2011 but are not included in averages by decade (the most recent of which is 2001-2010). Also, as other tables do, Table 1 presents the same data on changes over time in two ways—trends in annual values and comparisons of averages by decade to a baseline period of 1961-1990. As Table 1 shows, for example, total precipitation amounts averaged 4% below the baseline average in 1961-1970 but 9% above it in 2001-2010. (For a visual example of a trend in annual values, see Figure 2 on page 6; for a visual example of decadal comparisons, see Figure 1 on page 5.)

Probing deeper into these changes in precipitation, RMCO also analyzed storms of different sizes. This was done first by the simple metric of how much precipitation fell in a single day (see below through page 16). A second analysis focuses on storms in the top percentiles for amount of daily precipitation, determined individually for each weather station (see pages 17-18).

## STORMS BY SIZE

In analyzing storms by daily precipitation amounts, RMCO considered storms of four sizes—less than one inch in a day, at least one and less than two inches, at least two and less than three inches, and three inches and more. Table 2 below shows changes in key values for each category.

The first key point shown by Table 2 is also illustrated visually in Figure 1, on the next page: With each step up in the size of storms comprising

Changes in Frequency of and Precipitation from Storms by Size in the Midwest						
	Trend in Annual Values 1961-2011	Average Changes by Decade Compared to 1961-1990				
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010
<b>3-inches-plus storms:</b>						
Frequency	+103%	-14%	-3%	+17%	+20%	+52%
Precipitation	+108%	-14%	-3%	+17%	+20%	+55%
<b>2- to 3-inches storms:</b>						
Frequency	+81%	-3%	-11%	+15%	+13%	+30%
Precipitation	+77%	-3%	-11%	+14%	+12%	+30%
<b>1- to 2-inches storms:</b>						
Frequency	+34%	-6%	-1%	+8%	+9%	+13%
Precipitation	+36%	-6%	-1%	+8%	+10%	+14%
<b>Under 1-inch storms:</b>						
Frequency	+8%	-3%	+1%	+1%	+2%	+2%
Precipitation	+10%	-3%	+1%	+2%	+3%	+3%

Table 2. Frequency means the average frequency of storms of the indicated size per station per year. Precipitation means the total amount of precipitation from all storms of the indicated size per station per year. Trends are over 50 years. For frequency, the average changes by decade are the same as in Figure 1. See the Appendix for details on sources and methodology.

a category, the increase in frequency is greater. The largest of storms, those with three inches or more of precipitation in a day—called extreme storms in this report—had a statistical trend of a 103% increase in their annual frequency over 51 years.

Second, for all large storms, the increases accelerated over time, with the last analyzed decade, 2001-2010, having the greatest jumps. Again, the three-inches-plus storms had the biggest increase, with 52% more storms in 2001-2010 than in the baseline period.

The third key point shown by Table 2 is that the changes in storm frequency moved in nearly identical lockstep with the changes in precipitation amounts. For extreme storms, for example, the trend of a 103% increase in annual frequency between 1961 and 2011 nearly matches the trend of a 108% increase in total precipitation from all extreme storms in a year. For other categories of storm size, the

trends match even more closely.

Total precipitation would have differed more from storm frequency if the average size of individual storms within a category had changed notably over time. But the RMCO analysis (with this data not shown) indicates that the average storm sizes in each category varied little over the course of the study. For example, the size of extreme storms, compared to their 1961-1990 baseline, varied by only as much as a 1% decrease in 1991-2000 to a 2% increase in 2001-2010. In short, as measured in the RMCO analysis, there have been more large storms, but individual storms have not been larger. However, RMCO did not analyze storms lasting either a few hours or two or more consecutive days, which could have positive trends in average storm size.

Figure 1 below illustrates Table 2's data on changes in frequencies by decade for storms of different sizes.

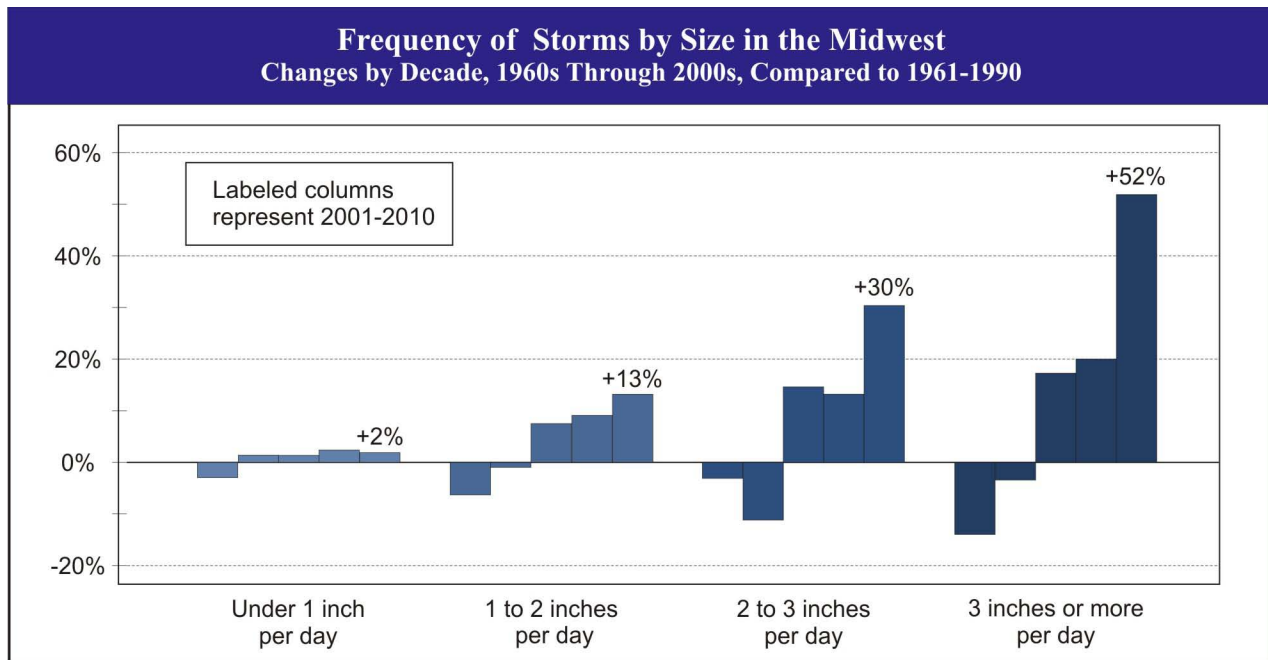


Figure 1. Changes by decade in the average frequencies per station per year of storms of different sizes, compared to the corresponding frequencies for 1961-1990. Storms are grouped by days with less than 1 inch of precipitation, at least 1 inch but less than 2 inches, at least 2 but less than 3 inches, and 3 inches or more. In each group, the columns from left to right represent 1961-1970, 1971-1980, 1981-1990, 1991-2000, and 2001-2010. The data represented here are also in Table 2. See the Appendix for details on sources and methodology.

**The RMCO analysis shows very clear patterns. The larger the storms, the more their frequency increased. And the increases have been greatest in recent years.**



## EXTREME STORMS: THE REGION

That extreme storms have increased in frequency in the Midwest so much more than other storms is very consequential, because of the damage these storms cause. In isolation, they can lead to flash floods, crop losses, and other damages.<sup>11</sup> When soils are already

saturated, river levels are high, or extreme storms come in rapid succession, they can cause widespread, sometimes devastating flooding (see Section 3 on pages 20-24).

Figure 2 below shows the average annual rates of extreme storms per single analyzed location in the Midwest for each year from 1961 through 2011, as

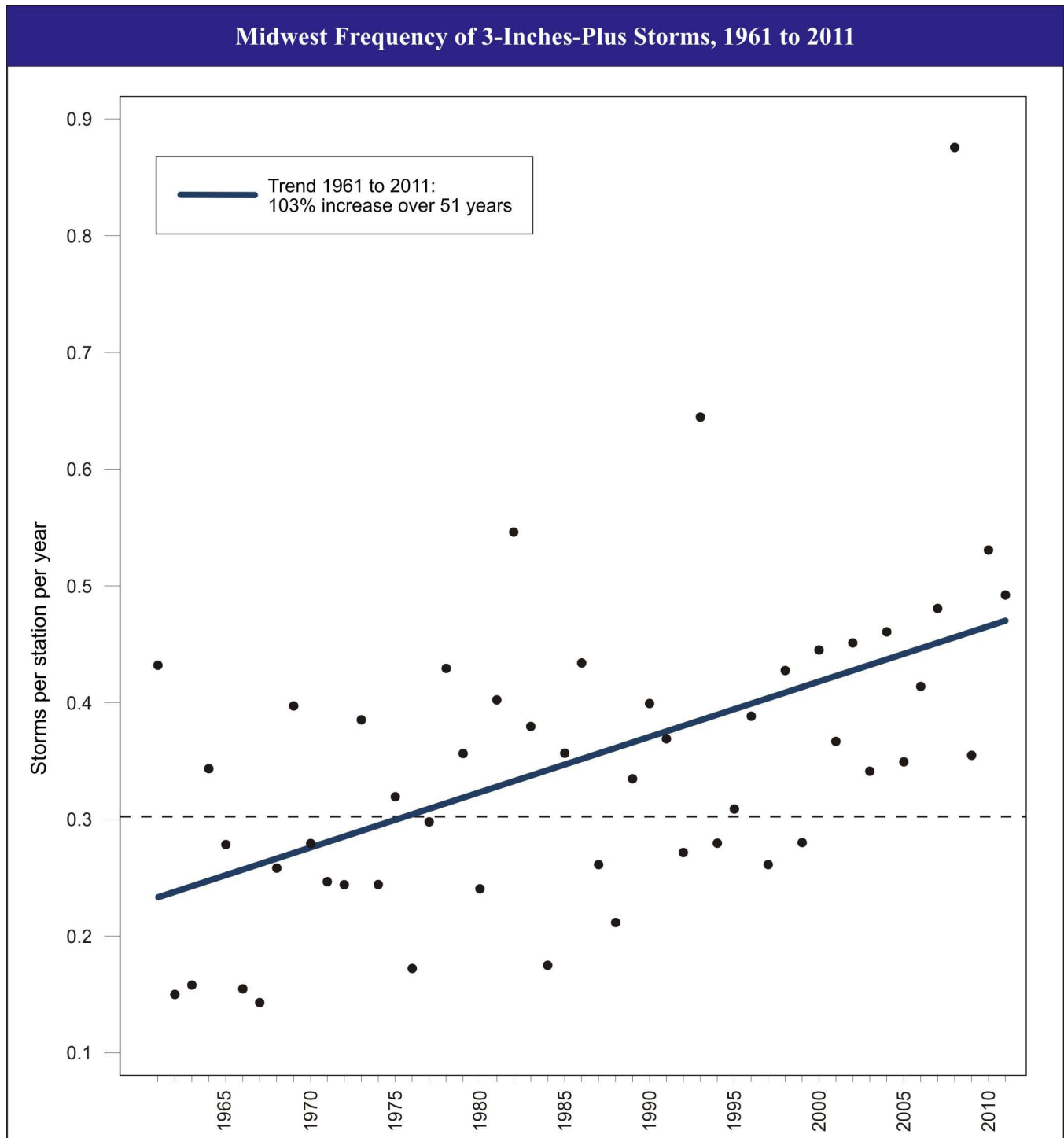


Figure 2. Average frequency of days with 3 inches or more of precipitation per station per year. Dots indicate annual values of average frequency per station, the blue line the 1961-2011 linear trend line, and the dashed line the average frequency from 1961 through 1990. See the Appendix for details of sources and methodology.

well as the linear trend in that frequency (previously shown in Table 2). As the figure shows, 2008 had the highest annual rate of extreme storms, by a huge margin. That year had nearly three times the average rate in the 1961-1990 baseline and also had 45% more extreme storms than the second-place year, which was 1993.

That 2008 and 1993 are the two years with the most extreme storms immediately suggests to Midwesterners the significance of these storms. Those who experienced them will never forget the enormous floods of 2008 and 1993, triggered by frequent and heavy rains, which rank near the top of natural disasters in United States history (see pages 20-22).

Table 3 below pulls together in one place the most important key regional results of the analysis of extreme storms. This table is exactly parallel to the tables (on pages 9-16) which present similar data on a state-by-state basis, enabling easy comparisons between the regional and state data.

Among the new data shown in Table 3 is a listing of

the top 10 years for the frequency of extreme storms and for the total amount of precipitation in a year from all extreme storms. As the table shows, of the top 10 years for frequency of extreme storms, the first 12 years of this century had seven. (In fact, this century has actually had seven of the top *nine* years.)

Also new in Table 3 is an additional way to understand the change in frequency of extreme storms—their return period, or the average length of time between two such storms. As the table shows, in the first decade of the analysis (1961-1970), extreme storms averaged once every 3.8 years at an individual location. That was two to four times more frequent than a major hurricane making landfall at a location along the U.S. coast from North Carolina to Texas.<sup>12</sup> In the last decade of the RMCO analysis, the average return period for midwestern extreme storms at a single location was down to 2.2 years. That is about four to eight times more frequent than landfalling major hurricanes.

3-Inches-Plus Storms in the Midwest							
	Trend in Annual Values 1961-2011	Average Changes by Decade Compared to 1961-1990					Top 10 Years 1961-2011 and Flooding Disasters(*)
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	
Frequency of 3-Inches-Plus Storms	+103%	-14%	-3%	+17%	+20%	+52%	(1) 2008* (6) 2007* (2) 1993* (7) 2000* (3) 1982* (8) 2004* (4) 2010* (9) 2002* (5) 2011* (10) 1961* 7 in this century
Return Period (in years)	-	3.8	3.4	2.8	2.8	2.2	-
Amount of Precipitation from All 3-Inches-Plus Storms	+108%	-14%	-3%	+17%	+20%	+55%	(1) 2008 (6) 2011 (2) 1993 (7) 2002 (3) 1982 (8) 1986 (4) 2010 (9) 1998 (5) 2007 (10) 2004 6 in this century

Table 3. Key results of analysis of days with at least 3 inches of precipitation. Frequency refers to the average number of days per station per year with 3-inches-plus storms. Return period refers to the average length of time between such storms. Amount of precipitation refers to the average amount of precipitation per station per year from all 3-inches-plus storms. Trends for 1961-2011 are in annual values over 51 years. The trend in the annual frequency of 3-inches-plus storms is the same data shown for those storms in Figure 1. Average changes by decade are the differences between decadal averages and the corresponding values for a baseline period of 1961-1990. The average change in frequency by decade is the same data shown in Figure 1 and in Table 2. The top 10 years are the years with the 10 highest values from 1961 through 2011 (and the rank of those years, out of 51 years). Data for 2011 are preliminary. See the Appendix for details on sources and methodology.

Figure 3 below is parallel to the figures (on pages 9-16) which display state-by-state changes by decade in the average frequency of three-inches-plus storms.

As with Table 3 on the previous page, the parallel presentation is intended to enable easy comparisons between regional and state data.

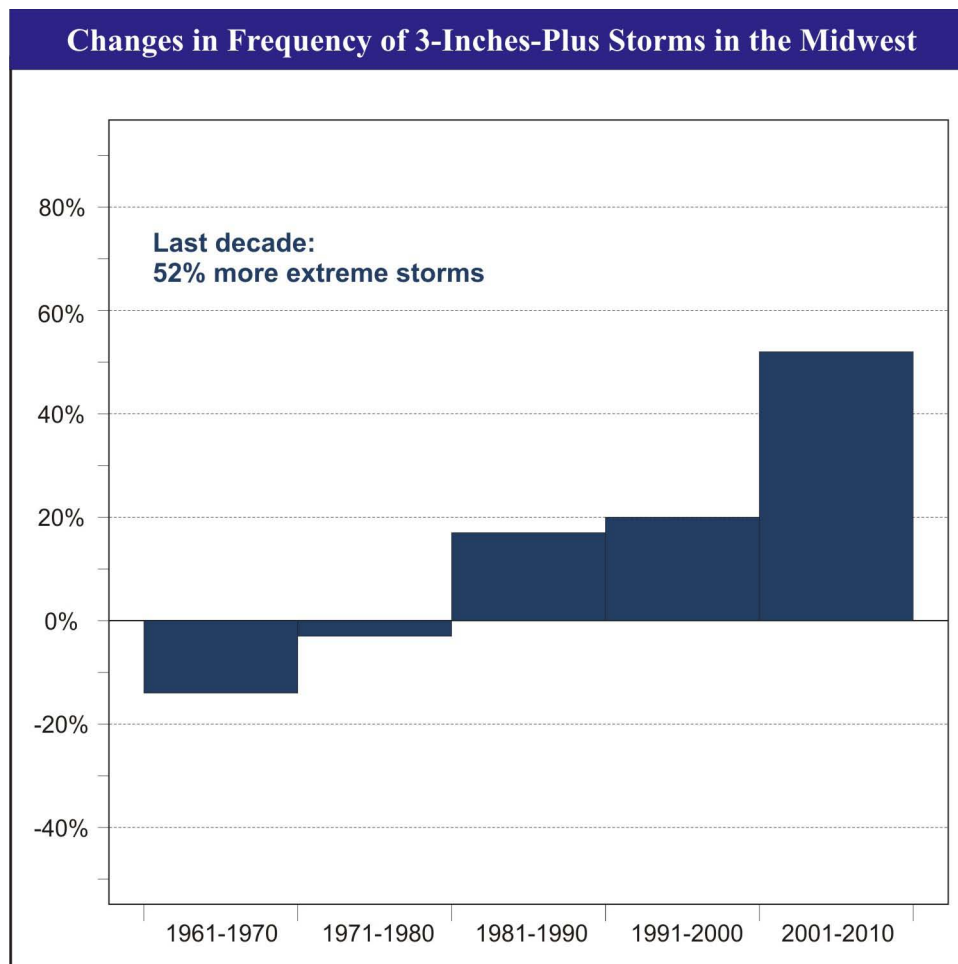


Figure 3. Changes by decade in the average frequencies per station per year of 3-inches-plus storms, 1961 through 2010, compared to the corresponding average frequencies for 1961-1990. The same data are shown in tables 2 and 3 and Figure 1. See the Appendix for details on sources and methodology.

## EXTREME STORMS: THE STATES

The RMCO analysis also includes state-by-state results for each of the eight midwestern states in our study, as shown in tables 4 through 11 and figures 4 through 11 on pages 9-16.

While the states show some variation in their results, they are generally consistent with the regional trends. In each state, the last analyzed decade (2001-2010) had the most extreme storms—in all but two cases (Illinois and Michigan) by a clear margin. Additionally, the state-by-state changes by decade in the total amount of precipitation from all extreme storms generally moved in close association

with changes in their frequency, again illustrating that the average size of storms within a category has not changed much over time.

The state results also suggest an additional insight to how the pattern of extreme storms has changed in the Midwest. The largest increases in extreme storm frequencies, both over the entire study period and in the last decade, have been in three of the states with relatively low average overall precipitation totals for this region: Michigan, Wisconsin, and Minnesota.

With fewer analyzed weather stations per state than in the region, the individual state trends expressed in the tables and illustrated in the figures are not necessarily statistically significant.

## ILLINOIS

3-Inches-Plus Storms in Illinois							
	Trend in Annual Values 1961-2011	Average Changes by Decade Compared to 1961-1990					Top 10 Years 1961-2011 and Flooding Disasters(*)
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	
Frequency of 3-Inches-Plus Storms	+83%	-1%	-20%	+22%	+24%	+26%	(1) 2008* (6) 2002* (2) 1993* (7) 1969* (3) 2011* (8) 2000 (4) 1982* (9) 1996* (5) 1961* (10) 1983* 4 in this century
Return Period (in years)	-	2.7	3.3	2.2	2.1	2.1	-
Amount of Precipitation from All 3-Inches-Plus Storms	+100%	-1%	-21%	+22%	+25%	+35%	(1) 2008 (6) 2002 (2) 2011 (7) 1969 (3) 1993 (8) 1996 (4) 1982 (9) 2000 (5) 1961 (10) 1983 4 in this century

Table 4. As Table 3 (on page 7) but with data only from stations in Illinois.

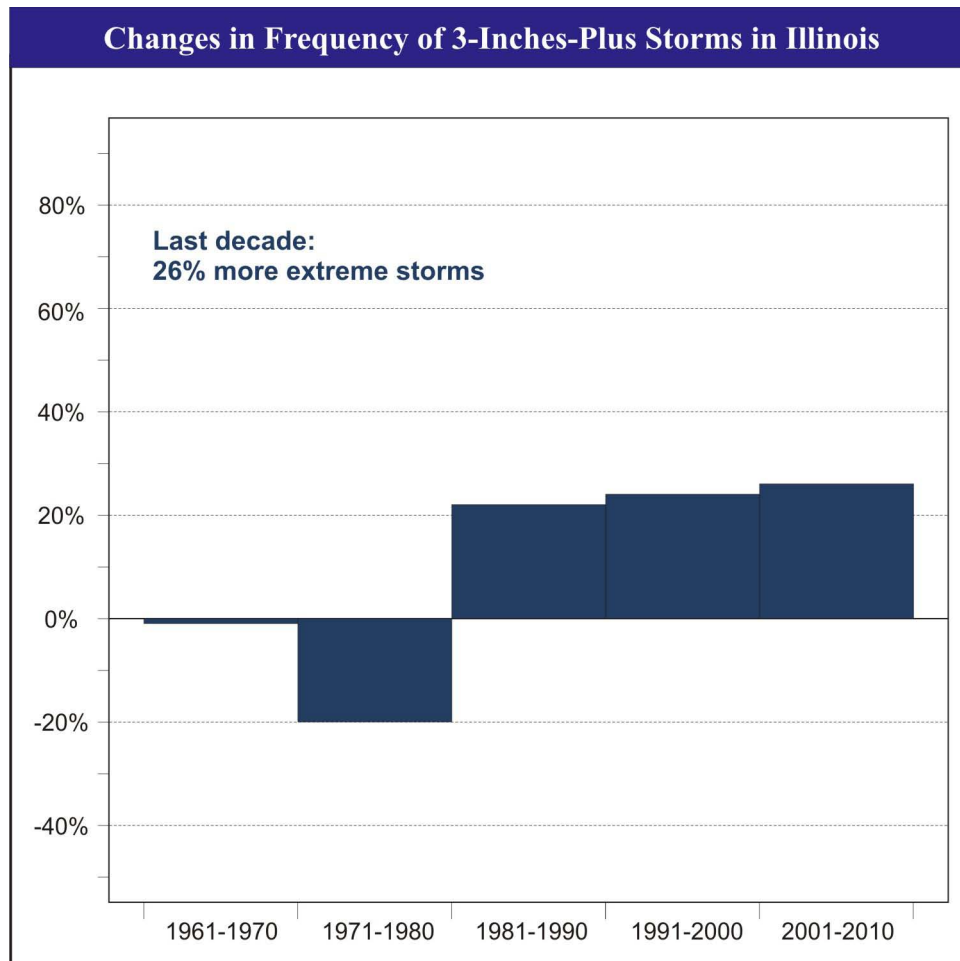


Figure 4. Comparisons to 1961-1990, as Figure 3 (on page 8), but only for Illinois stations.



## INDIANA

3-Inches-Plus Storms in Indiana							
	Trend in Annual Values 1961-2011	Average Changes by Decade Compared to 1961-1990					Top 10 Years 1961-2011 and Flooding Disasters(*)
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	
Frequency of 3-Inches-Plus Storms	+160%	-6%	-28%	+29%	+46%	+77%	(1) 2008* (6) 1990* (2) 1993* (7) 2001 (3) 1998* (8) 1981 (4) 1996* (9) 2006* (5) 2003* (10) 1961* 4 in this century
Return Period (in years)	-	3.5	4.5	2.5	2.2	1.8	-
Amount of Precipitation from All 3-Inches-Plus Storms	+159%	-6%	-29%	+30%	+46%	+75%	(1) 2008 (6) 1990 (2) 1996 (7) 1989 (3) 1993 (8) 2001 (4) 1998 (9) 1981 (5) 2003 (10) 2006 4 in this century

Table 5. As Table 3 (on page 7) but with data only from stations in Indiana.

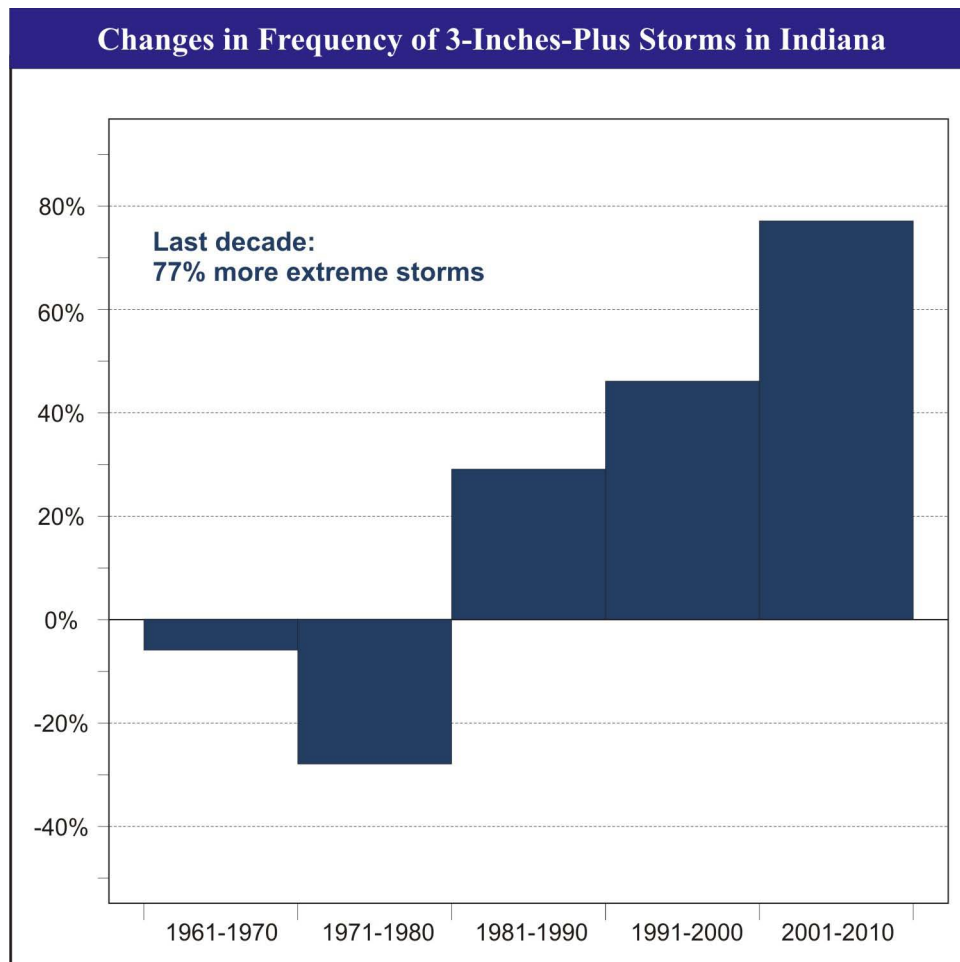


Figure 5. Comparisons to 1961-1990, as Figure 3 (on page 8) but with data only from stations in Indiana.

## IOWA

3-Inches-Plus Storms in Iowa							
	Trend in Annual Values 1961-2011	Average Changes by Decade Compared to 1961-1990					Top 10 Years 1961-2011 and Flooding Disasters(*)
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	
Frequency of 3-Inches-Plus Storms	+32%	-15%	+17%	-2%	-18%	+33%	(1) 2008* (6) 2010* (2) 2007* (7) 1993* (3) 1982 (8) 1990* (4) 1979 (9) 1974* (5) 1973* (10) 2004* 4 in this century
Return Period (in years)	-	2.9	2.1	2.6	3.1	1.9	-
Amount of Precipitation from All 3-Inches-Plus Storms	+35%	-12%	+16%	-5%	-21%	+34%	(1) 2008 (6) 1979 (2) 2007 (7) 1973 (3) 1982 (8) 1990 (4) 2010 (9) 1993 (5) 1962 (10) 1977 3 in this century

Table 6. As Table 3 (on page 7) but with data only from stations in Iowa.

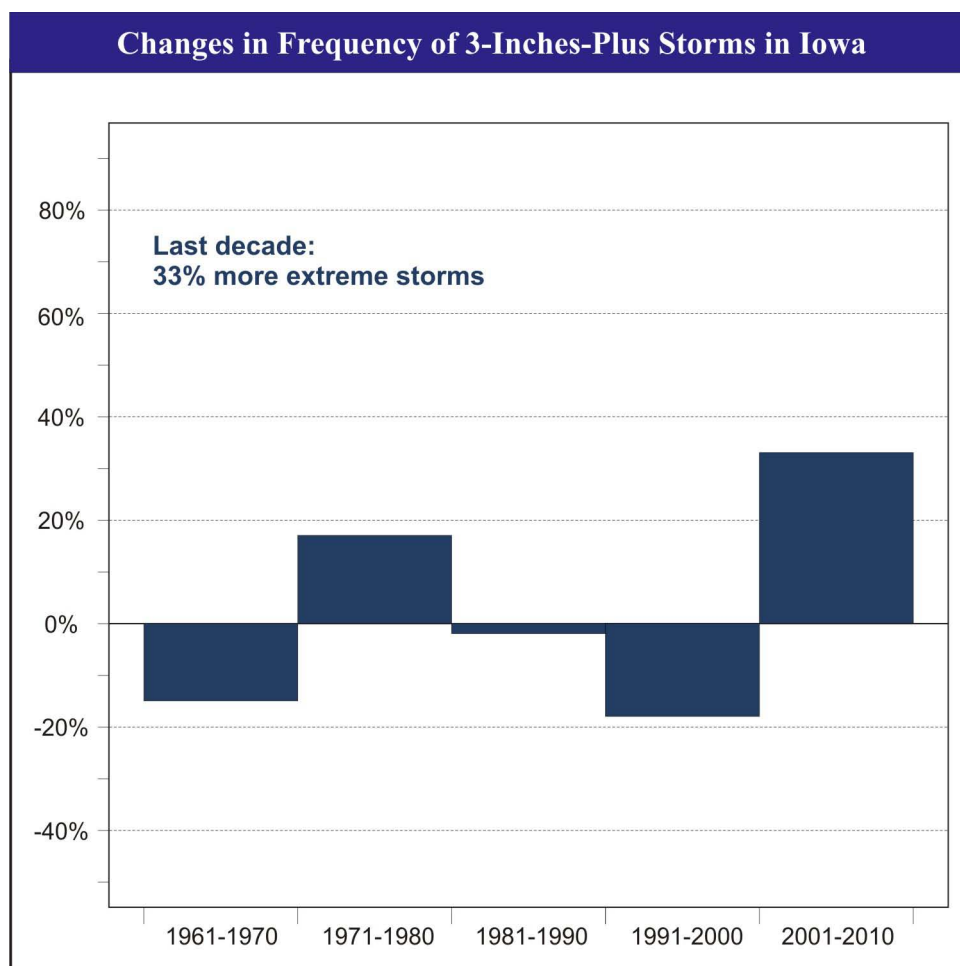


Figure 6. Comparisons to 1961-1990, as Figure 3 (on page 8) but with data only from stations in Iowa.

## MICHIGAN

3-Inches-Plus Storms in Michigan							
	Trend in Annual Values 1961-2011	Average Changes by Decade Compared to 1961-1990					Top 10 Years 1961-2011 and Flooding Disasters(*)
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	
Frequency of 3-Inches-Plus Storms	+180%	-45%	-6%	+52%	-3%	+54%	(1) 1986* (6) 2000* (2) 2001 (7) 2009 (3) 1975* (8) 1978 (4) 2008* (9) 1981 (5) 1982* (10) 1968 4 in this century
Return Period (in years)	-	14.4	8.4	5.2	8.1	5.1	-
Amount of Precipitation from All 3-Inches-Plus Storms	+160%	-50%	-5%	+54%	-6%	+39%	(1) 1986 (6) 2008 (2) 2001 (7) 2000 (3) 1975 (8) 2009 (4) 1978 (9) 1981 (5) 1982 (10) 1968 4 in this century

Table 7. As Table 3 (on page 7) but with data only from stations in Michigan.

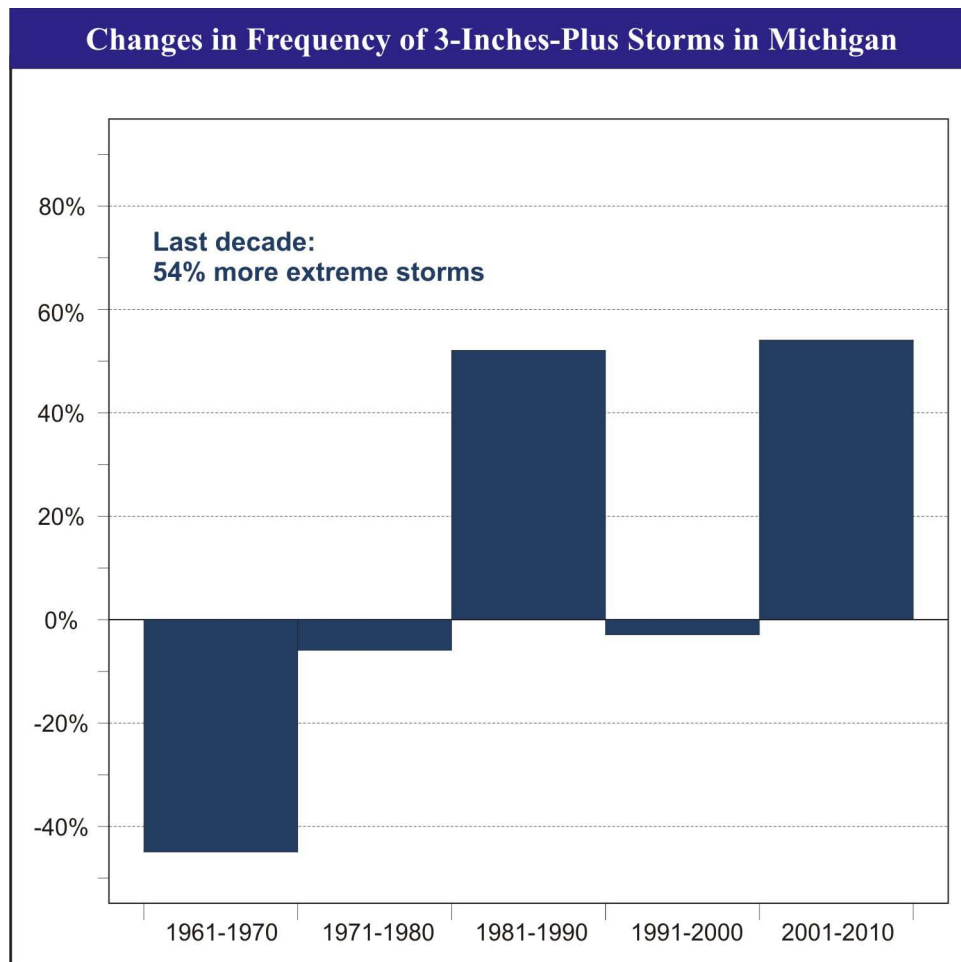


Figure 7. Comparisons to 1961-1990, as Figure 3 (on page 8) but with data only from stations in Michigan.

## MINNESOTA

3-Inches-Plus Storms in Minnesota							
	Trend in Annual Values 1961-2011	Average Changes by Decade Compared to 1961-1990					Top 10 Years 1961-2011 and Flooding Disasters(*)
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	
Frequency of 3-Inches-Plus Storms	+104%	-27%	+18%	+8%	+34%	+71%	(1) 2002* (6) 1991 (2) 2010* (7) 2000* (3) 1978* (8) 1995* (4) 2004* (9) 1973 (5) 2005 (10) 1981 5 in this century
Return Period (in years)	-	7.0	4.3	4.7	3.8	3.0	-
Amount of Precipitation from All 3-Inches-Plus Storms	+123%	-29%	+18%	+11%	+32%	+85%	(1) 2002 (6) 1995 (2) 1978 (7) 1993 (3) 2010 (8) 2000 (4) 2004 (9) 1981 (5) 2005 (10) 2006 6 in this century

Table 8. As Table 3 (on page 7) but with data only from stations in Minnesota.

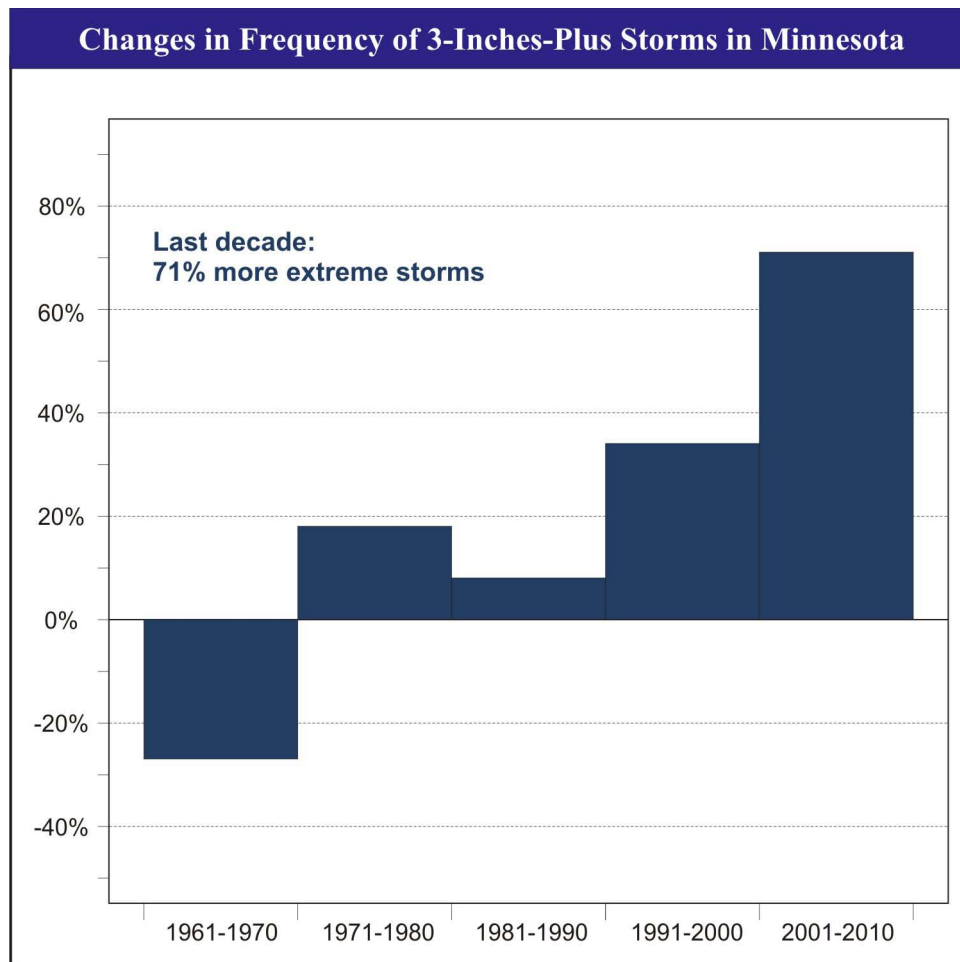


Figure 8. Comparisons to 1961-1990, as Figure 3 (on page 8) but with data only from stations in Minnesota.



## MISSOURI

3-Inches-Plus Storms in Missouri							
	Trend in Annual Values 1961-2011	Average Changes by Decade Compared to 1961-1990					Top 10 Years 1961-2011 and Flooding Disasters(*)
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	
Frequency of 3-Inches-Plus Storms	+81%	-9%	-12%	+22%	+24%	+39%	(1) 2008* (6) 1998* (2) 1993* (7) 2011* (3) 1982* (8) 1973* (4) 2009* (9) 1985 (5) 1986* (10) 2004* 4 in this century
Return Period (in years)	-	1.7	1.8	1.3	1.2	1.1	-
Amount of Precipitation from All 3-Inches-Plus Storms	+85%	-10%	-12%	+22%	+28%	+41%	(1) 2008 (6) 1998 (2) 1993 (7) 1973 (3) 1982 (8) 2011 (4) 1986 (9) 1961 (5) 2009 (10) 1985 3 in this century

Table 9. As Table 3 (on page 7) but with data only from stations in Missouri.

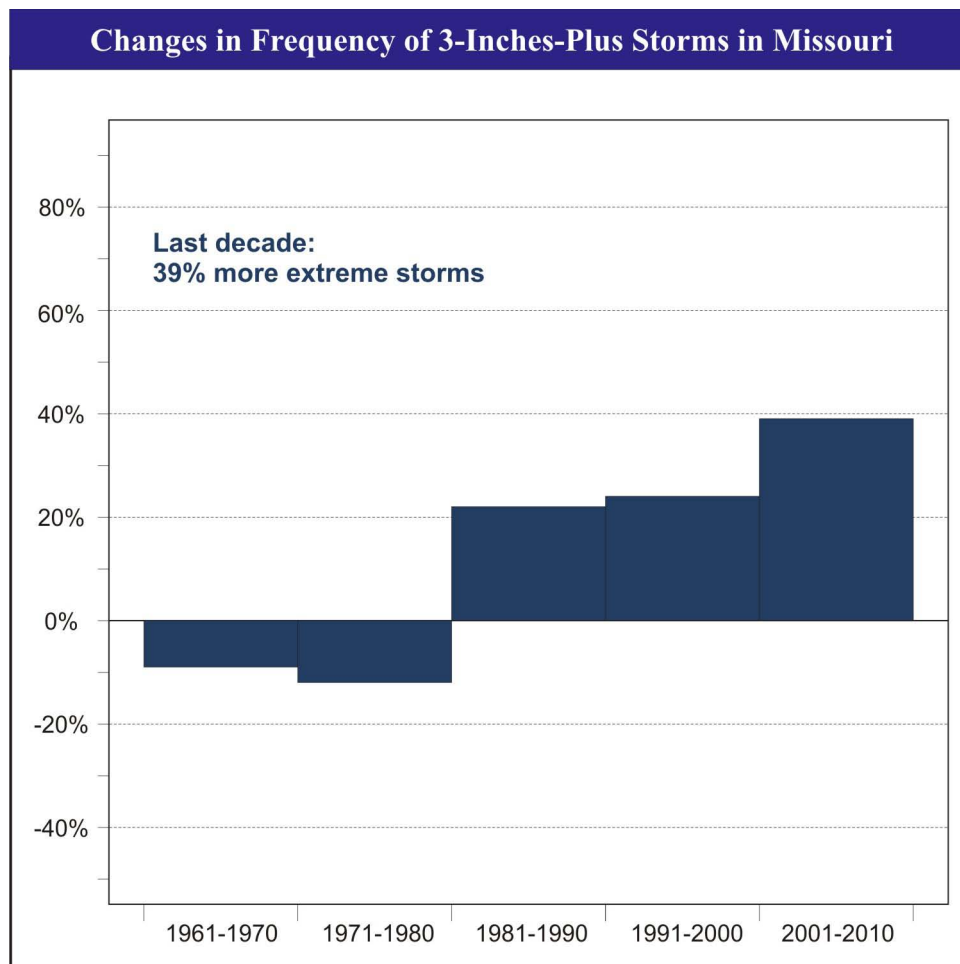


Figure 9. Comparisons to 1961-1990, as Figure 4 (on page 8) but with data only from stations in Missouri.

## OHIO

3-Inches-Plus Storms in Ohio							
	Trend in Annual Values 1961-2011	Average Changes by Decade Compared to 1961-1990					Top 10 Years 1961-2011 and Flooding Disasters(*)
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	
Frequency of 3-Inches-Plus Storms	+40%	-8%	+1%	+9%	-29%	+30%	(1) 1981* (6) 2004* (2) 2007* (7) 2006* (3) 1979 (8) 2010 (4) 1969* (9) 1965 (5) 1990* (10) 1997* 4 in this century
Return Period (in years)	-	6.1	5.5	5.1	7.8	4.3	-
Amount of Precipitation from All 3-Inches-Plus Storms	+29%	-2%	+1%	+3%	-35%	+30%	(1) 2007 (6) 1990 (2) 1981 (7) 2006 (3) 1969 (8) 1965 (4) 1979 (9) 2010 (5) 2004 (10) 1997 4 in this century

Table 10. As Table 3 (on page 7) but with data only from stations in Ohio.

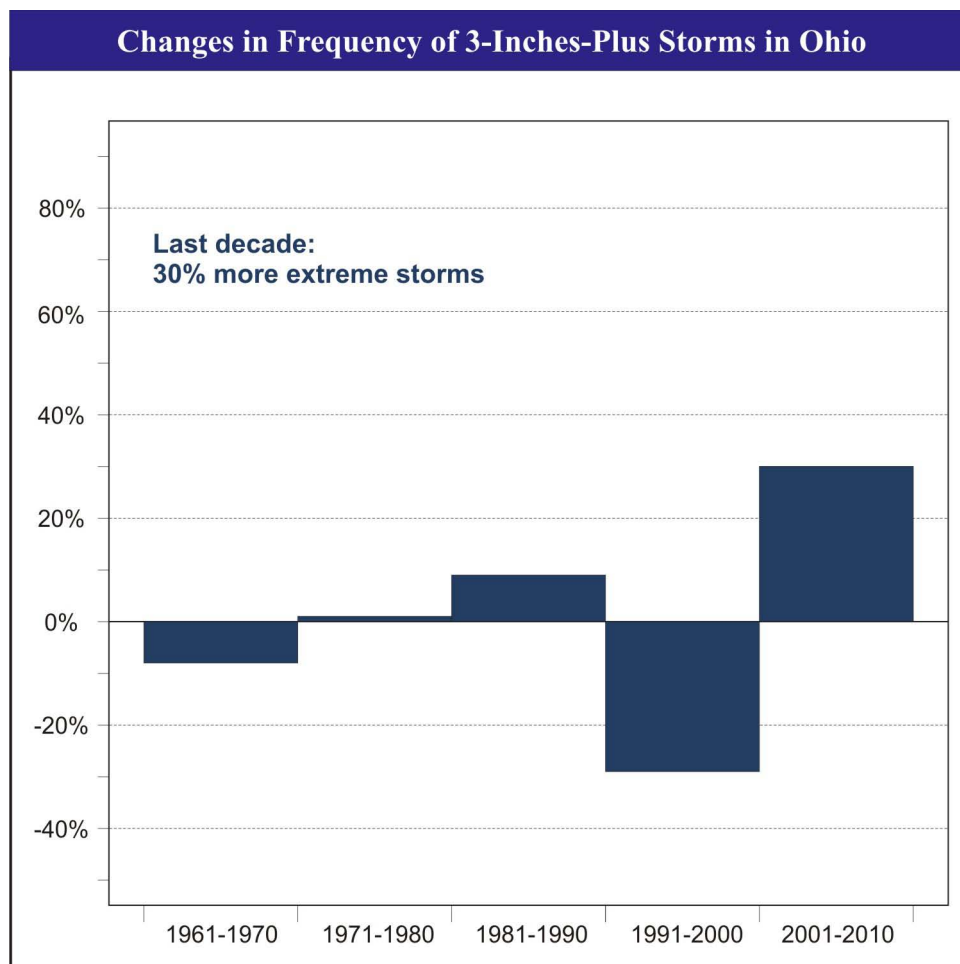


Figure 10. Comparisons to 1961-1990, as Figure 3 (on page 8) but with data only from stations in Ohio.

## WISCONSIN

3-Inches-Plus Storms in Wisconsin							
	Trend in Annual Values 1961-2011	Average Changes by Decade Compared to 1961-1990					Top 10 Years 1961-2011 and Flooding Disasters(*)
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	
Frequency of 3-Inches-Plus Storms	+203%	-30%	+25%	+6%	+54%	+92%	(1) 1978* (6) 2007* (2) 2008* (7) 1980* (3) 2010* (8) 2005 (4) 2000* (9) 1961 (5) 1991 (10) 2004* 6 in this century
Return Period (in years)	-	7.3	4.1	4.8	3.3	2.6	-
Amount of Precipitation from All 3-Inches-Plus Storms	+243%	-29%	+25%	+5%	+55%	+108%	(1) 1978 (6) 1991 (2) 2008 (7) 1980 (3) 2007 (8) 2005 (4) 2010 (9) 1993 (5) 2000 (10) 1961 5 in this century

Table 11. As Table 3 (on page 7) but with data only from stations in Wisconsin.

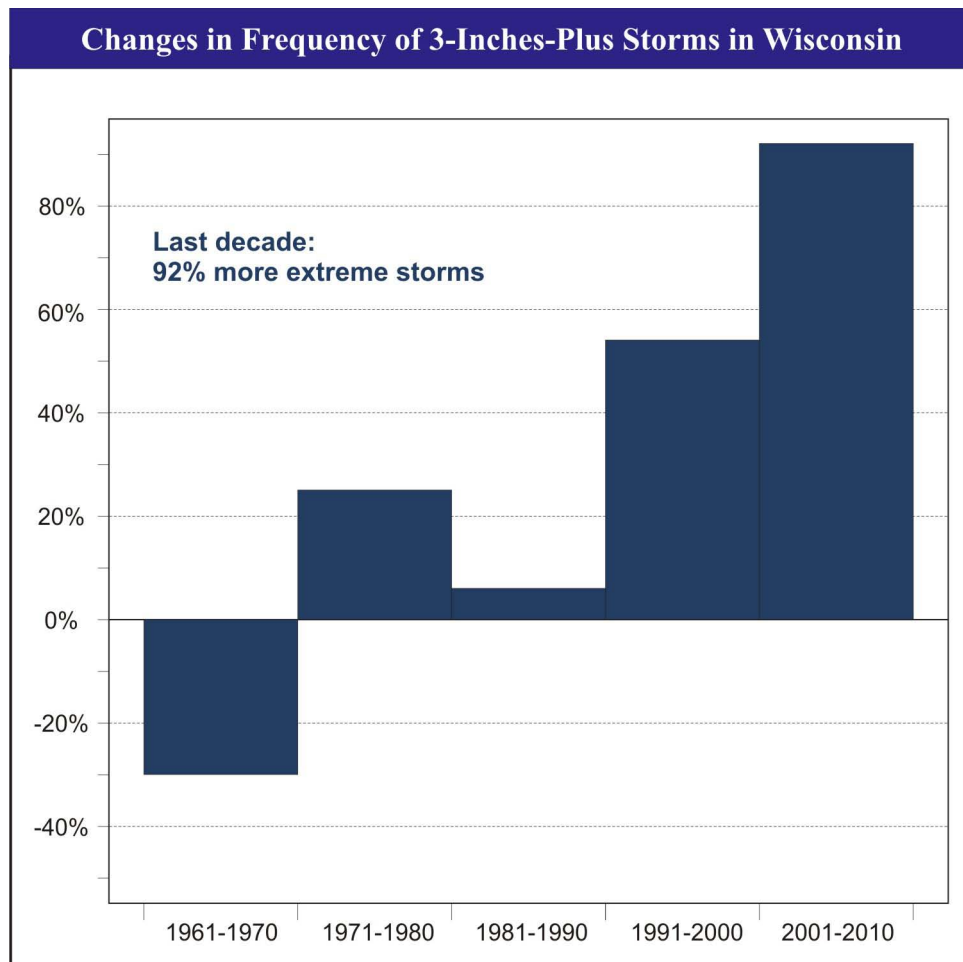


Figure 11. Comparisons to 1961-1990, as Figure 3 (on page 8) but with data only from stations in Wisconsin.

## PERCENTILE RANKINGS

As indicated on page 4, the RMCO analysis also examined trends in storms based on their rankings in the top percentiles of wet days. (For this part of the analysis, the preliminary 2011 data were not included.) Each station's thresholds for the top 0.3% and 1.0% wettest days were determined for a 1961-1990 baseline period, and days at that station above these thresholds was then tracked over time. For example, if 2.7 inches of precipitation per day were the threshold amount for the top 0.3% days at a particular station in 1961-1990, then all days with with that much precipitation were analyzed over the full period of 1961-2010, both as to their frequency and as to the amount of precipitation falling in them.

On a regional basis, the average threshold for the top 0.3% of storms was 2.95 inches of precipitation per day. That obviously is close to the three-inches threshold for the extreme storms discussed above, but because of local variation in precipitation intensity many stations have thresholds for top-0.3% storms that are quite a bit lower or higher than three inches. State averages for the 0.3% thresholds ranged from a low of 2.3 inches in Michigan to a high of 3.8 inches in Missouri (see page 34).

The percentile rankings have two advantages. This approach reflects local variation in precipitation intensity and analyzes the storms that are the heaviest in each area. Also, the percentile-ranking approach was used in previous studies presented in the U.S. government's 2009 national assessment (see page 1), and using this approach allows for a close comparison between the RMCO analysis and those studies (see pages 18-19).

As Table 12 below shows, the regional frequency of the largest of storms (the top 0.3%) increased much more than that of those not so large (the top 1.0%). This is consistent with the results of the analysis based on storm size (see page 4). Also, for both the top 0.3% storms and the top 1.0% storms, the changes in annual frequencies are much greater than are variations in the average amount of precipitation per storm (not shown). The changes in frequencies of these storms are therefore primarily responsible for the changes in total precipitation from all such storms in a year. This, too, is consistent with the results of the analysis based on absolute storm size (see page 5).

The 1961-2010 trends shown below are statistically significant with a 95% level of confidence (see pages 34-35).

Changes in Heaviest Storms by Percentile Rankings in the Midwest						
	Trend in Annual Values 1961-2010	Averages by Decade Compared to 1961-1990				
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010
Top 0.3% Storms						
Change in frequency of the storms	+89%	-12%	0%	+12%	+21%	+45%
Change in precipitation from the storms	+99%	-12%	-1%	+13%	+20%	+51%
Top 1.0% Storms						
Change in frequency of the storms	+59%	-9%	-7%	+16%	+16%	+29%
Change in precipitation from the storms	+66%	-9%	-6%	+16%	+16%	+35%

Table 12. Data from 1961 through 2010. For explanation of the percentile rankings, see the text. Frequency is the average number of days per station per year with storms of the indicated rankings. Precipitation is the average total amount of precipitation per station per year from all storms of the indicated rankings per station. In the first data column, the trends are per 50 years. In the other columns, the percentages are comparisons to the corresponding values for 1961-1990. See the Appendix for sources and methodology.



Table 13 below presents data on the changes in frequencies of top-0.3% storms on a state-by-state basis. Again, with fewer stations in a single state,

the state trends are not necessarily statistically significant.

Frequency of Top 0.3% Storms in Midwestern States						
	Trend in Annual Values 1961-2010	Average Changes by Decade Compared to 1961-1990				
		1961-1970	1971-1980	1981-1990	1991-2000	2001-2010
Illinois	+64%	+2%	-19%	+16%	+30%	+23%
Indiana	+170%	-5%	-19%	+22%	+47%	+82%
Iowa	+38%	-10%	+14%	-4%	-23%	+41%
Michigan	+92%	-25%	-9%	+35%	-3%	+34%
Minnesota	+81%	-18%	+22%	-4%	+32%	+51%
Missouri	+93%	+3%	-23%	+20%	+39%	+46%
Ohio	+49%	-8%	+5%	+4%	+6%	+19%
Wisconsin	+146%	-27%	22%	+6%	+40%	+61%

Table 13. As Table 12, but only for top 0.3% storms, and showing results on a state-by-state basis.

## PREVIOUS SCIENTIFIC STUDIES

Several previously published scientific studies, although not using such recent data, are consistent with the general conclusions of the RMCO analysis—including that total precipitation in the Midwest has increased over the past half century, that large storms have increased in frequency more than small ones, and that the largest of storms have increased the most.

The methodology for the RMCO analysis (see the Appendix on pages 32-35) was deliberately designed to enable comparison to two figures in the U.S.

government's 2009 national assessment of climate change impacts (see page 1). Those figures show regional trends in the frequency of top 1% storms and in the amount of precipitation falling in them, and results are reported for the Midwest, defined to mean the same eight states as in the RMCO analysis.<sup>13</sup> The figures show that the Midwest had the second largest regional increases in the both the frequency of top 1% storms and precipitation amounts from them, behind only the Northeast.

Table 14 below compares the data in the national assessment figures and from the RMCO analysis on the top 1% storms. A perfect comparison is not

Top 1.0% Storms in the Midwest Comparison of 2009 National Assessment with RMCO Analysis			
Analysis	Time Period	Trends over 50 years	
		Frequency	Precipitation
National Assessment	1958-2007	+27%	+31%
RMCO (partial)	1961-2007	+50%	+53%
RMCO (complete)	1961-2010	+59%	+66%

Table 14. Source for national assessment data: U.S. Global Change Research Program.<sup>14</sup> For more information on the national assessment data, the studies on which they are based, and the sources and methodology of the RMCO analysis, see the Appendix.

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possible because the period covered by the results in the national assessment begins with 1958, and the RMCO analysis begins three years later. The data in the national assessment also goes through only 2007. For a closer comparison, the table shows RMCO results both for a partial period of 1961-2007 and for 1961-2010.

As the table shows, the partial RMCO analysis for 1961-2007 shows much more of an increasing trend than the national assessment data for 1958-2007. Contributing to this could be the different starting years for the datasets, the different weather stations that were analyzed, and that in the RMCO analysis questionable daily records were excluded (see page 33).

More generally, several studies have documented increases in heavy precipitation in the Midwest, although none yet published have assessed data through 2011 as the RMCO analysis does. Also, none other than the national assessment have used a methodology particularly close to the RMCO analysis.

For example, in 1991, three scientists published perhaps the earliest study showing that the Midwest has seen a larger increase in extreme precipitation than most of the contiguous United States.<sup>15</sup>

In 1997, another study found that in the eight midwestern states plus Kentucky there had been about a 20% increase over the period 1901-1994 in the frequency of days with at least two inches of rainfall.<sup>16</sup>

The Wisconsin Initiative on Climate Change Impacts reported that the frequency and magnitude of heavy rainfall events have increased in that state. Madison, for example, had nine days with three inches of precipitation in the last decade, compared to a high of three such days per decade out of the five previous decades.<sup>17</sup>

On a global and national level, many other studies document that in recent decades overall precipitation has increased somewhat and that large storms have increased at a greater rate. As a 2008 U.S. government interagency scientific report summarized, "All studies indicate that changes in heavy precipitation frequencies are *always* higher than changes in precipitation totals and, in some regions, an *increase* in heavy and/or very heavy precipitation occurred while no change or even a decrease in precipitation totals was observed."<sup>18</sup>

**"One of the clearest precipitation trends in the United States is the increasing frequency and intensity of heavy downpours. . . . During the past 50 years, the greatest increases in heavy precipitation occurred in the Northeast and the Midwest."**

U.S. Global Change Research Program<sup>19</sup>

### 3. EXTREME STORMS AND FLOODS

Extreme storms are consequential to the Midwest primarily because they can lead to destructive flooding in the region—either flash floods or, especially when the extreme storms come in quick succession, widespread flooding.

Floods are to the Midwest what hurricanes are to the Atlantic coast areas—the region’s most widely destructive type of regularly occurring natural disaster. Across the United States, flooding is the second most costly type of natural disaster, ranking behind hurricanes but ahead of drought, earthquakes, coastal disasters (including storm surges, coastal flooding, erosion), tornadoes, and other types of natural disasters.<sup>20</sup> And much of the Midwest is more susceptible to flooding than most of the country.<sup>21</sup>

#### WORST EXTREME-STORM YEARS

The five years that topped the RMC analysis for years out of 1961-2011 for the frequency of extreme storms also had widespread, destructive flooding.

The two worst years for extreme storms were also the two years with the most catastrophic midwestern flooding, by far, since 1961. In 2008, flooding across

Floods in the Midwest can be among the nation’s worst natural disasters. New evidence presented here ties the increasing frequency of extreme storms with major floods of recent years in the region.

the region caused \$15.8 billion in damages.<sup>22</sup> The Great Flood of 1993 was even worse, with \$32.8 billion in damages, making it the fifth costliest natural disaster in the United States since 1980. Only the worst of hurricanes are comparable. Since 1980, only hurricanes Katrina and Andrew were costlier than the Great Flood of 1993. Only they and five other major hurricanes were costlier than the flooding of 2008.

**Since 1961, the two years with the most extreme storms in the Midwest also had the region’s worst flooding.**

The fourth-place year for frequency of extreme storms, 2010, had heavy storms that caused approximately \$1 billion in damage to corn and soybean crops in Iowa alone.<sup>23</sup> The fifth-place year, 2011, was also notable for its flooding, which caused an estimated \$2 billion in damage, making it the second most destructive year for midwestern flooding since 1980.<sup>24</sup>

Also telling is the incidence of federal disaster designations based on flooding in the years with the most extreme storms. In 2008, seven of the eight midwestern states had flooding disasters.<sup>25</sup> In 1993, six states did; in 1982 (the third-place year) and 2010, five did; and in 2011, six did.

That years with high numbers of extreme storms have also had extensive flooding supports the common-sense connection between the two. The remainder of this section presents new evidence linking extreme-storm frequency and floods in the Midwest.



FEMA/Andrea Booher

St. Genevieve, Missouri, 1993.



## ANALYSIS OF 2008 STORMS

The RMCO analysis identifies for the first time the contribution extreme storms made to the worst midwestern flooding in 2008.

The National Climatic Data Center documented that the worst floods of 2008 were caused by “copious amounts of rainfall” in June of that year in Iowa, Wisconsin, Illinois, and Indiana, on ground saturated from heavy winter and spring precipitation.<sup>26</sup> In those states from June 7 through June 9, 11 official records were set for the most rainfall in any single day in the history of a weather station.<sup>27</sup>

For this report, RMCO assessed how much of the June 2008 precipitation that triggered the midwestern floods came from storms meeting this report’s definition of extreme storms—three inches or more of precipitation in a single day.

As the Midwestern Regional Climate Center map in Figure 12 below shows, from June 1 through June 15 several areas received totals of a foot or more of rainfall.<sup>28</sup> The most devastating flooding across the region was precisely in these areas or just downstream of them.<sup>29</sup>

RMCO analyzed daily precipitation records for all weather stations within the areas shown in Figure 12 where 12 inches or more of rain was reported in June 1-15. The results are in Table 15 on the next page. As the table shows, nearly half of all rain in the areas of the heaviest June 1-15 rainfall came from three-inches-plus storms. Without the extreme storms, in other words, the areas with the most extreme rainfall would have had much more manageable totals of precipitation.

Of all 36 three-inches-plus storms in the analyzed areas, 28 occurred from June 7 through 9, the peak of the storms that caused the major flooding. These storms were heavy ones, even for extreme storms, with daily rainfall amounts averaging 4.3 inches, more than 10% above the average total for a midwestern extreme storm in 1961-1990.

But the frequency of these extreme storms is the real story. Weather stations in these areas of the heaviest downpours averaged 1.3 extreme storms in 15 days. That is more than 100 times above the region’s average frequency of 0.3 extreme storms per location per year from 1961 through 1990. Without the extremely frequent extreme storms, the flooding would not have been nearly so bad.

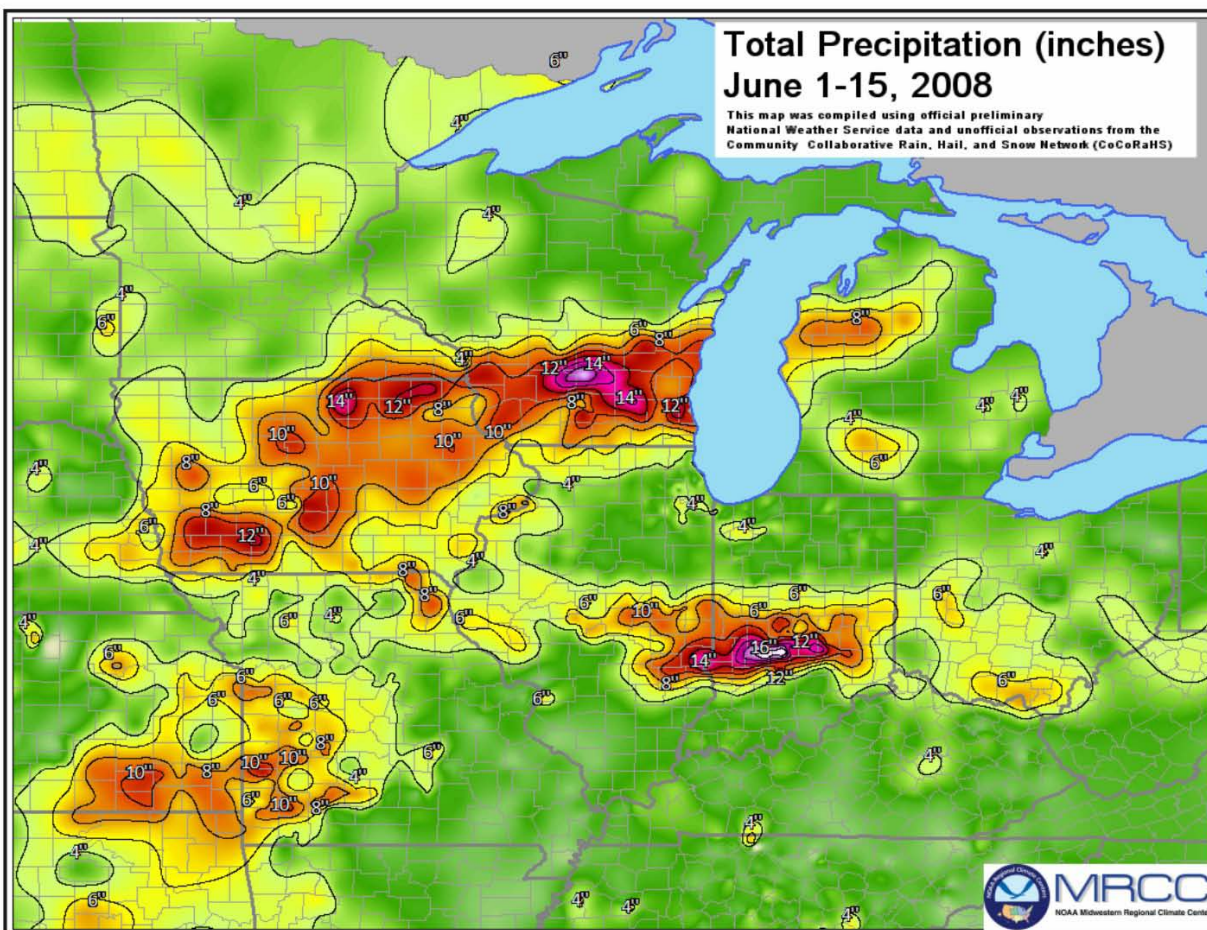


Figure 12. Source: Midwestern Regional Climate Center.<sup>30</sup>

### Contribution of 3-Inches-Plus Storms in Areas With Heaviest June 1-15, 2008, Precipitation

Average total precipitation per station	Average number of 3-inches-plus storms per station	Average precipitation per 3-inches-plus storm	Average precipitation per station from 3-inches-plus storms	Average share of total precipitation per station from 3-inches-plus storms
11.9 in	1.3	4.3 in	5.7 in	48%

Table 15. Data from 27 weather stations within areas shown in Figure 11 as having 12 inches or more of rainfall in June 1-15, 2008. See the Appendix for sources and methodology.

The storms and flooding of June 2008 illustrate one of the key problems of an increasing frequency of extreme storms: The cumulative effect of

extreme events in quick succession can be especially devastating.<sup>31</sup>

## JUNE 2008 FLOODING IN COLUMBUS, INDIANA

A U.S. Geological Survey report details the extreme storm and resulting flooding in central and southern Indiana in June 2008—the flooding experienced by Babe and Jeanie Herron in Columbus, Indiana’s hardest-hit city (see page 1).<sup>32</sup> The flooding was set up by saturated ground and high streams, resulting from rains earlier in the year. As much as three inches of rain had fallen on May 30–31 and five inches on June 3–4. Then, on June 6, abnormally moist air from the Gulf of Mexico ran into a stationary front across south-central Indiana, causing frequent to nearly

continuous rainfall and thunderstorms from about 6:00 p.m. that day until about 1:00 p.m. on June 7. Upstream of Columbus in the basin of the East Fork White River, Edinburgh received an unofficial but credible total of 10.71 inches of rain on June 7, a storm so large it could be expected only about once every 1,000 years.

That Edinburgh rainfall also unofficially tops the state’s official 24-hour rainfall record of 10.5 inches, which dates back to 1905.<sup>33</sup>

In six hours on June 7, the East Fork White River at Columbus surged to a near-record peak stage. The next day, the river hit its high mark, 18.61 feet, breaking a record set in 1913.<sup>34</sup> The USGS estimated that the peak flow of Haw Creek, which flows into the river at Columbus, was 65% greater than that of a 100-year flood. It was Haw Creek’s flooding which caused most of the local damage.<sup>35</sup> The flooding happened so quickly that people had as little as 15 minutes to evacuate their homes and businesses.<sup>36</sup>

The first floor and basement of the Columbus Regional Hospital were flooded, forcing the evacuation of 157 patients and causing \$125 million in damage. About 15% of all structures in Columbus were flooded, and more than 70 local businesses suffered flood damage. There were two local deaths from the flooding.<sup>37</sup>



Columbus Regional Hospital, Columbus, Indiana, 2008.



## CORRELATIONS OF STORMS, FLOODS

For a further test of the correlation between the frequency of extreme storms and significant flooding, RMCO tallied for each of the eight midwestern states the instances of flooding destructive enough to qualify for federal disaster declarations, in the top five years, middle five years, and lowest five years for extreme-storm frequency in that state. As Table 16 below

shows, the more extreme storms there were, the more flood disasters there also were.

With different pieces of evidence connecting the frequency of extreme storms in the Midwest to floods, and with scientists attributing the global increase in heavy precipitation to human disruption of the climate (see page 25), the Midwest must be considered increasingly vulnerable to flooding as human alteration of the climate continues to grow, as Section 4 explains.

<b>Extreme Storms and Flood Disasters in Midwestern States</b> <b>Based on Each State's Rankings of Extreme-Storm Frequency</b>			
	Years with Flood Disasters in High, Medium, and Low Years for Extreme Storms		
	Top 5 Years	Middle 5 Years	Bottom 5 Years
Illinois	5 years	3 years	2 years
Indiana	5 years	2 years	0 years
Iowa	4 years	1 year	1 year
Michigan	4 years	2 years	2 (of 8) years
Minnesota	4 years	2 years	3 years
Missouri	5 years	4 years	1 year
Ohio	4 years	4 years	2 years
Wisconsin	4 years	2 years	1 year
Total	35	20	12

Table 16. "Flood disaster" indicates whether there was at least one federal declaration of a disaster based on flooding in a year in a particular state. Data source: Federal Emergency Management Agency.<sup>38</sup> Rankings of top 5, middle 5, and bottom 5 years are from each state's rankings out of 51 years, 1961-2011, for the annual frequency of 3-inches-plus storms per station in that state. For Michigan, 8 years tied as the lowest (with no 3-inches-plus storm). See the Appendix for details and sources on storm frequency.



Cedar Rapids, Iowa, 2008.

## HEALTH EFFECTS OF EXTREME STORMS AND FLOODS

Tolls of the damages from extreme storms and floods sometimes include fatalities and injuries, but these usually are counts of drownings, vehicle accidents, and other immediate injuries. Less reported but often more numerous are illnesses and even deaths from consumption of contaminated water. According to a U.S. government report, floods can lead to transmission of water-borne diseases, both directly by contaminating freshwater sources with untreated or partially treated sewage, and indirectly by causing the breakdown of water supply and sewage treatment infrastructure facilities.<sup>39</sup> Over half of all waterborne disease outbreaks (mainly intestinal disorders from contaminated drinking water) in the United States are caused by storms in the top 10% of precipitation magnitude, and over two-thirds by storms in the top 20%.<sup>40</sup>

An extreme example was in Milwaukee in 1993, when 54 people were killed and over 400,000 sickened by water contaminated by a disease-causing parasite. Heavy storms are believed to have washed the parasite into Lake Michigan (a source of drinking water) from overflowing drainage systems and water-treatment facilities.<sup>41</sup> Beyond the lives lost, other costs of this single outbreak included \$31.7 million in medical costs and \$64.6 million in productivity losses.<sup>42</sup>

The Midwest is particularly at risk because many of its cities rely on combined sewer systems, an older design that mingles storm water and sewage in the same pipes. During heavy rains, these

systems often cannot handle the volume, and raw sewage spills into lakes or waterways, including drinking-water supplies and places where people swim.<sup>43</sup> Combined sewer overflows (CSOs) can contain a variety of dangerous pollutants, including bacteria, toxic chemicals, pesticides, oil and grease, sediment, nutrients, and trash, all of which can harm water quality.<sup>44</sup> In the Midwest, sources of drinking water (including the Great Lakes) that are vulnerable to CSOs are relied upon by more than 40 million people, including residents of Chicago, Milwaukee, Detroit, and Cleveland.<sup>45</sup>



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## 4. MORE POLLUTION, MORE TROUBLE

The increase in extreme storms documented in this report is part of a global increase in heavy precipitation that scientists have said stems from human disruption of the natural climate. Scientists also project that if emissions of heat-trapping pollution continue to grow, then further increases in big storms will result, especially in the Midwest.

### ATTRIBUTION TO HUMAN-CAUSED CLIMATE CHANGE

Human actions already are changing the climate and an increase in heavy precipitation is one of the results, according to many scientific reports.<sup>46</sup>

For years, scientists have pointed out that under the laws of atmospheric physics higher air temperatures should lead to more extreme precipitation. Those higher temperatures and the role of humans in causing them are now well-established. The U.S. government's national assessment of climate-change impacts (see page 1) opens with these two sentences:

Observations show that warming of the climate is unequivocal. The global warming observed over the past 50 years is due primarily to human-induced emissions of heat-trapping pollutants.<sup>47</sup>

This echoes the Intergovernmental Panel on Climate Change (IPCC), which in 2007 said there is more than a 90% likelihood that humans have caused most of the temperature increases over the last 50 years.<sup>48</sup> The national assessment and the IPCC also report that the world would have cooled since 1950 from natural factors, except they were trumped by heat-trapping pollution.<sup>49</sup> The last 17 years include all of the 16 hottest years since 1880.<sup>50</sup>

The national assessment also tells us that, as a result of "very basic physics," warmer air holds more moisture than cooler air does, increasing the likelihood for extreme precipitation when a storm does occur in a hotter climate.<sup>51</sup> Scientists therefore have expected that with temperature increases will come a larger change in extreme precipitation than in median precipitation.<sup>52</sup> Observations of this projected change—across the planet, in the United States, and in the Midwest (see pages 18-19)—have added to the confidence of scientists that human influences are

The Midwest's increases in extreme storms have occurred within the context of increasing human disruption of the climate. Scientists have recently concluded that global increases in heavy precipitation are driven by human-caused changes in the climate. Scientists also project that extreme precipitation will continue increasing, including in the Midwest.

already changing Earth's climate.<sup>53</sup>

In 2011, Seung-Ki Min and others published the

**"The increase in heavy precipitation events is associated with an increase in water vapor, and the latter has been attributed to human-induced warming."**

U.S. Climate Change Science Program<sup>54</sup>

first study demonstrating a causal relationship between human increases in heat-trapping gases and increases in heavy precipitation.<sup>55</sup> They based their conclusions on a "fingerprinting" technique of climate scientists—using climate models and statistical analysis to separate the likely influences of heat-trapping pollutants from natural climate variability. Comparing observed precipitation extremes at 6,000 Northern Hemisphere weather stations from 1951-1999 with simulated reconstructions for the same time period by multiple climate models, they found that:

"[H]uman-induced increases in greenhouse gases have contributed to the observed intensification of heavy precipitation events found over approximately two-thirds of data-covered parts of Northern Hemisphere land areas."<sup>56</sup>

Detecting a clear human role in changing extreme precipitation patterns at a smaller geographic scale is much more difficult, and scientists have not yet reported any such conclusions for the Midwest or

any similar subcontinental areas.<sup>57</sup> With respect to flooding caused by extreme precipitation in the United Kingdom in the fall of 2000, scientists have performed a “detection and attribution” study showing that the likelihood of that flooding having occurred was approximately doubled by human influences on the climate.<sup>58</sup>

Although scientists have not yet been definitive that human alteration of the climate is responsible for changes in extreme-storm frequency and flooding in the Midwest, the number of dots that can be connected is rising. As stated above, human-caused changes to the climate are driving global increases in heavy precipitation. Also, the Midwest is a region where the increases have been greater than in most of the rest of the United States (see pages 18-19). The frequency of Midwestern extreme storms appear correlated to major floods in the region (see pages 20-23). Finally, as a leading scientist, Kevin Trenberth, recently wrote, when the question is whether an extreme event is caused by human-driven climate change, “The answer is that all weather events are affected by climate change because the

environment in which they occur is warmer and moister than it used to be.”<sup>59</sup>

**A threshold may already have been crossed, so that major floods in the Midwest perhaps now should no longer be considered purely natural disasters but instead natural/unnatural disasters.**

## FUTURE EXTREME STORMS

Scientists consistently project that heavy storms will continue getting stronger, at a greater rate than we have yet experienced, with the increase in heavy precipitation continuing to be greater than in overall precipitation.<sup>60</sup> The higher the levels of future emissions of heat-trapping gases, the greater the changes in heavy precipitation are projected to be.<sup>61</sup> Figure 13 below, taken from the U.S. government’s 2009 national assessment report, illustrates this.<sup>62</sup>

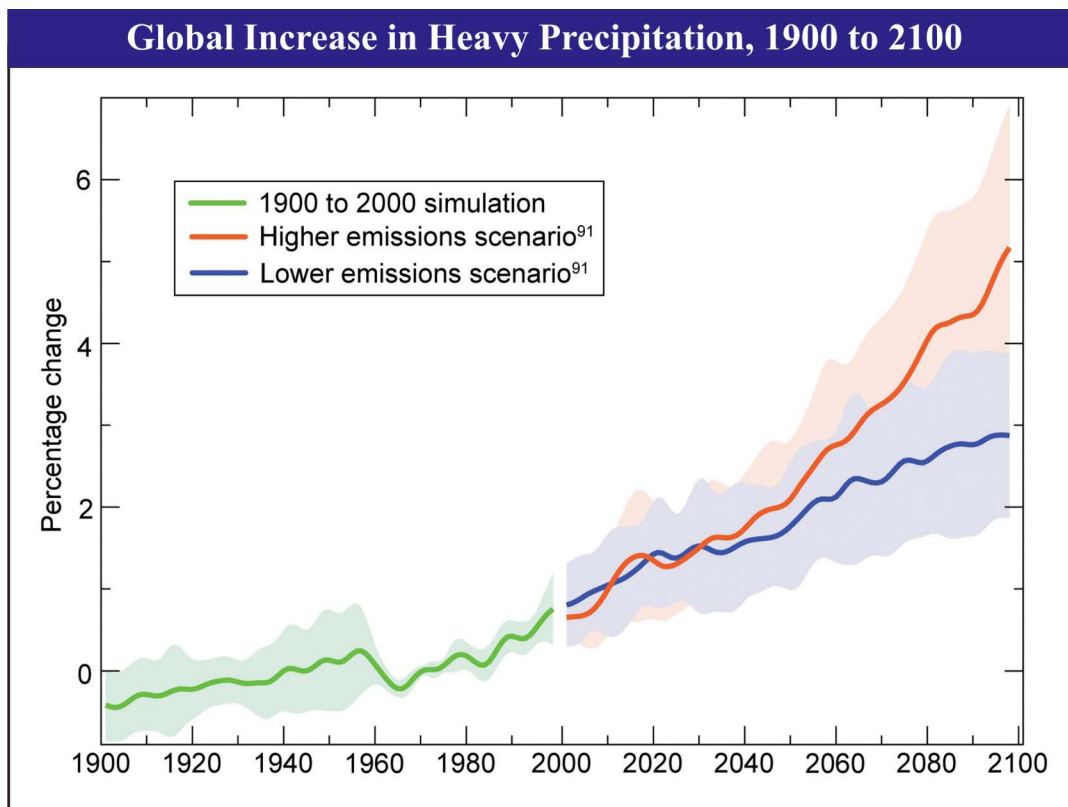


Figure 13. Simulated (prior to 2000) and projected (after 2000) changes in the global amount of precipitation falling in the heaviest 5% of daily events. The shaded areas show the likely ranges while the lines show the central projections from a set of climate models. Changes are relative to the 1960-1979 average. Figure source: U.S. Global Change Research Program.<sup>63</sup>

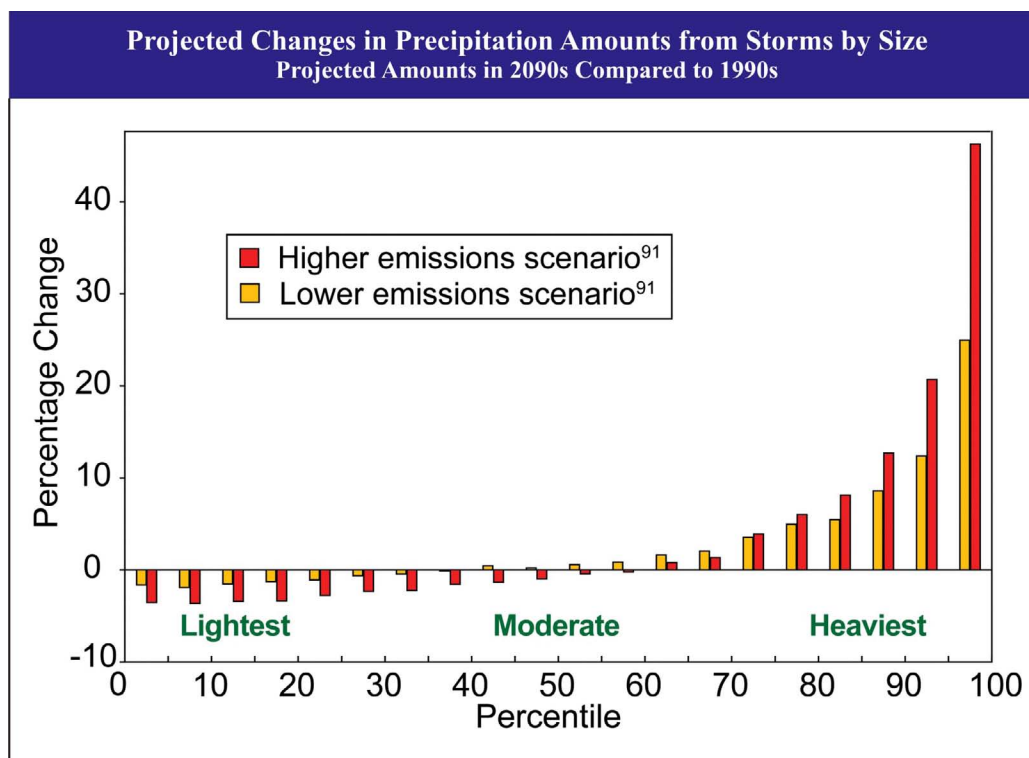


Figure 14. Projected changes in amounts of precipitation in the 2090s from storms of different sizes, compared to the amounts from such storms in the 1990s. Each pair of columns is for a category of storm size, in increments of 5%, from small storms on the left to the heaviest on the right, based on percentile rankings of storms by size in the 1990s. Each pair of columns shows average projections from multiple climate models, with the gold based on lower future emissions of heat-trapping gases and the red based on higher emissions. Under either scenario, precipitation amounts from lighter storms are projected to decrease and from heavier storms to increase, with greater changes if emissions are higher. The farthest-right columns, for example, show that in the 2090s the amount of precipitation from storms of a size representing the top 5% of storms in the 1990s could increase by nearly 40% with higher future emissions compared to more than 20% with lower emissions. Figure source: U.S. Global Change Research Program.<sup>64</sup>

The U.S. government's national assessment report includes another figure, reproduced above, that illustrates in a different way how future changes in heavy precipitation depend on future emission levels.<sup>65</sup> It shows that total precipitation from storms of the size that in the 1990s qualified as the top 5% could increase by well over 40% by the end of this century, if future emissions of heat-trapping pollution are relatively high. If future emissions are held down, the rate of increase could be about half as much, but still would be significant.

The importance of future emissions means that the extent to which strong storms keep getting stronger depends to a large extent on what we humans do. (See page 28 and Section 5 on pages 29-31.)

In the Midwest, heavy precipitation is expected to increase more in the future than in most of the country, just as the Midwest has already had a greater increase in heavy precipitation than most of the country (see pages 18-19).<sup>66</sup> According to a U.S.

government scientific report, midwestern storms so extreme that they now happen only once every 20 years are projected to occur every four to six years near the end of the century.<sup>67</sup>

Other studies also suggest that extreme precipitation in the Midwest will increase. For example, the Wisconsin Initiative on Climate Change Impacts has projected that in that state the frequency of three-inches-plus storms will continue increasing more than the rate of smaller storms.<sup>68</sup> The extent of future changes is expected to depend on future emissions of heat-trapping gases, as shown in Table 17 on the next page. If emissions are higher, greater increases in frequency are projected for all large storms, especially late in the century, as the table shows. The average size of the heaviest rainfall events is also projected to increase somewhat. For example, a 100-year event (now about five to seven inches in 24 hours) could become about 10% larger.



## Average Projected Changes in Frequency of Large Storms in Wisconsin Compared to 1961-2000

	2046-2065		2081-2100	
	Lower Future Emissions	Medium-High Future Emissions	Lower Future Emissions	Medium-High Future Emissions
3-inches-plus storms	+31%	+34%	+39%	+66%
2-inches-plus storms	+21%	+24%	+26%	+43%

Table 17. Averages of projections from multiple climate models. The numerical values are estimates by RMCO of the values represented by columns in figures by the Wisconsin Initiative on Climate Change Impacts.<sup>69</sup>

As the Wisconsin report points out, making a distinction between changes in storm frequency and changes in storm intensity (which this report also does), is uncommon in the scientific literature, which typically lumps both changes together.<sup>70</sup> Making the distinction is important because increasingly frequent strong storms can have different impacts than isolated but larger storms.<sup>71</sup> (See pages 23-24.)

scenarios, none of which assume new policies to ward off climate change. The U.S. government's 2009 national assessment report, for example, pointed to a "stabilization" scenario that has the potential to hold further global temperature increases below an additional 2°F and avoid dangerous climate change.<sup>74</sup> The key point is that with new policies designed to reduce heat-trapping pollution, we can, in fact, realize a better future—if we choose to. (See page. 31)

## THE IMPORTANCE OF REDUCING EMISSIONS

That future levels of heat-trapping pollutants will play a major role in determining the extent of further increases in heavy storms illustrates the importance of reducing emissions to avoid unacceptable climate changes.

Future emission levels will result from many variables, the most important being the extent to which we humans decide to limit our climate-changing pollution. In making projections about the extent of future climate changes, scientists use different scenarios of possible future emissions of heat-trapping pollution. Those scenarios, some of which are illustrated in Figure 15, themselves illustrate how much room there is for us to reduce emissions.

When the scenarios now being used were developed in the 1990s, global emissions of heat-trapping gases were increasing by about 1.1% per year; since then, however, emissions have been much higher, so the current scenarios could understate how much we will continue changing the climate.<sup>72</sup> Scientists are now developing new scenarios with a broader range of possible future emission levels.<sup>73</sup>

The good news, on the other hand, is that future emissions could be well below any of the current

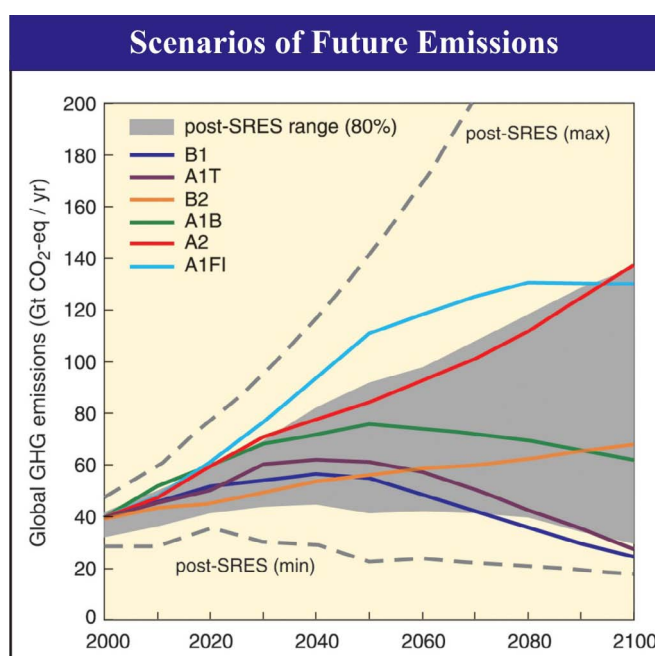


Figure 15. Annual levels of emissions of heat-trapping gases of selected current emissions scenarios. Dashes indicate the range of new ("post-SRES") scenarios being developed, with the gray area representing the middle 80th percentile of that range. Figure from the IPCC.<sup>75</sup>

## 5. TOWARD A BETTER FUTURE

The increased frequency of large storms in the Midwest and the costly flooding that often accompany them demonstrate the need for action on two fronts. First, actions are needed to prepare for and increase resiliency to extreme storms and floods. Second, we need to reduce emissions of the heat-trapping pollution that is already disrupting our climate, so that further increases in extreme weather and other changes are kept to acceptable levels.

*The remainder of this section is contributed by Theo Spencer, Natural Resources Defense Council.*

### PREPARING FOR EXTREMES

As this report makes clear, extreme weather events—especially large storms—will continue to be part of living in the Midwest. To deal with this reality, there are a host of actions that must be taken at the federal, state, and local levels. One important area for actions is increasing emergency preparedness, both for individuals and civic entities, to reduce loss of life and damages when extreme storms and flooding occur. Another important area, the focus of this subsection, should be reducing the extent to which our buildings, roads, and sewage systems actually increase the dangers of storms and floods. Because the built infrastructure of our country often consists of significant impervious areas, rainfall can run off developed land in amounts that cause or increase pollution problems and flooding. Further development and application of “green-infrastructure” strategies can reduce these problems.

In general, green infrastructure refers to approaches that restore or mimic natural conditions, allowing rainwater to infiltrate into the soil or evapotranspire into the air, as well as to rainwater harvesting. Green-infrastructure techniques include porous pavement, green roofs, street trees, roadside plantings, and rain barrels. Such approaches reduce the risk of flooding, while also preventing pollution, by minimizing the amount of rainwater that flows into sewer systems and increasing the amount that is absorbed by soil and plant materials. These smarter water practices on land also beautify neighborhoods, cool and cleanse the air, reduce asthma and heat-

Actions at the federal, state, and local levels can prepare the Midwest to reduce the future impacts of more extreme storms. Ultimately, to avoid ever-increasing weather extremes, heat-trapping pollution must be limited, and the federal government must lead the way.

related illnesses, save on heating and cooling energy costs, boost economies, and support American jobs.

### Federal Action

While the U.S. Environmental Protection Agency (EPA) recognizes the importance of green infrastructure, it can do more to fully integrate green infrastructure into its permitting and regulatory programs. Most importantly, EPA must reform the national Clean Water Act rules that apply to stormwater sources to require retention of a sufficient amount of stormwater through infiltration, evapotranspiration, and rainwater harvesting to ensure water-quality protection and reduce flooding risk. The agency should also ensure that all future Combined Sewage Overflow consent orders and/or long term control plans incorporate green infrastructure. And because EPA has responsibility for overseeing (and, in a few states, implementing) the Clean Water Act’s permitting program, it should enforce existing regulations governing discharges from municipal separate storm-sewer systems to make sure that green infrastructure is deployed in order to reduce pollutant discharges to the maximum extent practicable and to address local water-quality needs.

The U.S. Department of Transportation must also provide guidance and funding to address the role that roads and highways play in increasing local flooding, as well as increasing pollutants into waterbodies. For example, recipients of federal transportation dollars should be required to use green infrastructure to protect waterbodies.

With a forecasted need of hundreds of billions

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of dollars of infrastructure investments, the Administration and Congress must better support the Clean Water Act's Clean Water State Revolving Fund (CWSRF). The CWSRF provides critical dollars to help states repair and rebuild failing water and wastewater infrastructure as well as storm-system protection and watershed and estuary management. Unfortunately, the Administration's proposed budget includes approximately \$1.18 billion for the CWSRF, a 19.8% reduction from the approximately \$1.47 billion enacted in fiscal 2012.<sup>76</sup>

## State Action

States also have a critical role in promoting green infrastructure. One way to do this is by integrating it into state guidance and regulatory actions. Much as transportation planners link roads, highways and bridges, states should develop green-infrastructure plans that connect natural systems to maximize ecological and environmental benefits, as well as reduce the risk of flooding and water contamination. States should also develop and enforce permitting programs that require the use of green infrastructure, and ensure that building and other development-related codes and standards do not pose an unreasonable barrier to green infrastructure. State-funded agencies should require state-funded roadway projects to retain a certain amount of the runoff generated by their impervious surfaces. States can also increase funding options available for green-infrastructure projects. For example, states should eliminate hurdles to use available funding sources, such as CWSRF, for alternative water infrastructure, such as green infrastructure. These funds typically favor wastewater programs above others; in some states, green infrastructure and similar projects that promise more flexibility and resilience in the face of changing precipitation trends do not receive the same priority as more traditional approaches. Other revenue streams can be found, such as (in New York) real-estate transfer fees and bond acts (Los Angeles). States can also authorize retrofit-financing programs which accelerate investment in green-infrastructure retrofits.

## Local Action

There are a number of actions cities should undertake to protect communities and maximize their green-infrastructure investments, such as:

- Develop a long-term green infrastructure plan that lays out a vision for how green infrastructure will be implemented across a city. Preventing stormwater runoff from occurring is the most effective way to minimize pollution and reduce the total volume of water

that sewer systems must capture and treat. Minimizing impervious surfaces, preserving existing vegetation, and incorporating green space into urban-design projects all decrease water pollution and reduce flooding risk. Binding targets for reduction of the percentage of impervious surfaces should be implemented (Philadelphia has binding five-year targets as part of its 25-year *Green City, Clean Waters* plan<sup>77</sup>).

- Ensure a dedicated funding stream for green infrastructure. Many cities charge private properties a stormwater fee based on the amount of impervious surface area on the property, while also giving a credit to those adopting resilient practices.
- Develop and enforce a strong retention standard for stormwater, and require the use of green infrastructure to reduce or otherwise manage runoff from existing impervious surfaces.
- Provide incentives for residential and commercial private-party use of green infrastructure, such as fast-tracking the permit application of projects that incorporate green roofs and other green features and for properties with a very high percentage of their impervious surfaces disconnected from the sewer system. Several cities also have grant programs, property-tax credits and low-interest loans to facilitate green-infrastructure practices on private land.
- Provide guidance or other affirmative assistance to accomplish green infrastructure. Examples include local demonstration projects, workshops, design and construction assistance, handbooks on overcoming code and zoning barriers, and free rain barrel distribution. The most common technical barriers to more widespread use of green infrastructure are uneven knowledge, and lack of experience about green-infrastructure design, maintenance and benefits.
- Create an inventory of critical infrastructure at risk due to flooding. Priorities in the short term should be the identification of critical facilities at risk (such as roads, hospitals, drinking-water supplies and conveyance systems, sewage treatment, and conveyance infrastructure) so as to inform longer-term planning, construction, funding, and other resiliency goals. Identifying this critical infrastructure should be based on available information and refined as improved data become available.
- Protect critical infrastructure and require

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utilities to conduct vulnerability assessments of their systems. Ensuring climate-ready utilities is a key aspect of preparing any community for climate change. Local plans should be strengthened by encouraging and, where possible, requiring water- and energy-utility operators to prepare and update their own site- and system-specific vulnerability assessments, which should include addressing utility vulnerability to flooding.

- Identify and protect critical habitat. Protecting critical habitat provides multiple benefits by providing natural buffers for human infrastructure and important refuge for plants and animals that may be at risk from climate change.
- Pursue nonstructural solutions and exploit natural protective features to address problems such as flooding. Nonstructural solutions such as the strategic acquisition of land, buffer zones, wetlands, and open space preservation all create multiple benefits that local governments should encourage as options to address concerns about flooding.

## PREVENTING CLIMATE DISRUPTION

Ultimately, to protect the Midwest from even more severe storms in the long term, each of us must look to reduce emissions of heat-trapping pollutants in our daily lives. The federal government must lead the way, with broad, aggressive actions on five essential fronts:

- Enacting comprehensive mandatory limits on global warming pollution to reduce emissions by at least 20% below current levels by 2020 and 80% by 2050. This will deliver the reductions that scientists currently believe are the minimum necessary, and provide businesses the economic certainty needed to make capital investments to achieve those reductions.
- Protecting the current Clean Air Act authority of the U.S. Environmental Protection Agency (EPA). This includes current authority under the

Clean Air Act to set standards to curb global warming pollution from vehicles, power plants, and large industrial sources. EPA authority must also be maintained to institute the tightest pollution controls necessary to protect public health and the environment. That includes standards for the pollution that causes smog and other dangerous and fatal respiratory ailments, pollution of hazardous materials like mercury and dioxin, and dangerous waste from power plants and other industrial facilities.

- Overcoming barriers to investment in energy efficiency to lower emission-reduction costs, starting now. To fully harness energy-efficiency potential, many opportunities require additional federal, state, or local policies to unleash investments that are already cost-effective even without a price on greenhouse-gas emissions. Policies include building, industry, and appliance efficiency (standard) upgrades, as well as incentives for “smart” transportation and growth and for advanced vehicles.
- Accelerating the development and deployment of emerging technologies to lower long-term emission reduction costs. That means incentives and investments in renewable electricity, low-carbon fuels, and carbon capture and storage; a federal renewable-energy standard; and infrastructure upgrades to support transmission capacity for these renewable assets.
- Finally, regulations are needed to require that, to the extent that any new coal-fired power plants are built, those plants capture and permanently geologically sequester at least 85% of their carbon-dioxide emissions, along with state and federal regulatory frameworks for site selection, operation, monitoring, and liability for carbon-capture and geologic-storage systems. Any such new coal plants would also need to be held to stringent standards for controlling their other pollution emissions, source coal only from companies using less destructive mining techniques (which includes, but is not limited to, not relying on mountaintop removal), and ensure that their waste is disposed of safely.

**“Future climate change and its impacts depend on choices made today. The amount and rate of future climate change depend primarily on current and future human-caused emissions of heat-trapping gases and airborne particles. Responses involve reducing emissions to limit future warming, and adapting to the changes that are unavoidable.”**

U.S. Global Change Research Program<sup>78</sup>

## APPENDIX

### SOURCES AND METHODOLOGY FOR 1961-2011 ANALYSIS

This portion of the Appendix details the sources and methodology for the RMCO analysis of precipitation data for the 1961-2011 period, as reported in Section 2.

As indicated at different points in this Appendix, the RMCO analysis was substantially patterned after the methodologies of previous scientific studies of trends in heavy precipitation in the United States and in the Midwest by scientists at the National Climatic Data Center (NCDC), a division of the National Oceanic and Atmospheric Administration. Those previous studies are the foundations for the data presented in the 2009 national assessment (see page 1), and using parallel elements of their methodologies enabled the comparison shown on pages 18-19.

#### Weather Stations

RMCO analyzed daily precipitation data for 1961 through 2011 from 218 midwestern weather stations in the U.S. Historical Climatology Network (USHCN). The data through 2010 were obtained from the USHCN and have been subjected to quality controls; USHCN data for 2011 are not yet available and for that year preliminary data from the same weather stations were used for some elements of the RMCO analysis (see below).

The USHCN is a network developed by NCDC of the nation's highest-quality weather stations, with a dataset of quality-controlled daily and monthly records intended to assist in the detection of regional climate change.<sup>79</sup> The most important elements of USHCN are the selection of the weather stations in the network and the evaluation of the data reported from the stations. USHCN stations were chosen using a number of criteria including length of record, percentage of missing data, number of station moves and other station changes that may affect data homogeneity, and resulting network spatial coverage, all to enable accurate detection of trends representing the nation, regions, and states.

Daily precipitation data from the USHCN network have been used by others for detection of precipitation trends.<sup>80</sup> The 218 USHCN stations included in the RMCO analysis were selected from the 227 USHCN stations in the eight midwestern states, with nine excluded because the stations were not in operation early enough for this analysis. Those excluded stations are in Perry, IL; Crawfordsville, Huntington, and Vincennes, IN; Chatham, MI; Eveleth, Marcell, and Olivia, MN; and Truman Dam,

MO. The remaining USHCN stations that were included in the RMCO analysis are summarized in the following table.

U.S. Historical Climatology Network Weather Stations in RMCO Analysis	
Midwest	218
Illinois	35
Indiana	33
Iowa	23
Michigan	23
Minnesota	30
Missouri	25
Ohio	26
Wisconsin	23

Table App-1.

Of course, this sample of 218 stations across the Midwest is not sufficient to capture all precipitation events in the region. This is especially so for intense precipitation, which exhibits greater local variability than other extreme phenomena, so that the heaviest area of precipitation in a storm may fall between stations.<sup>81</sup> But a total of 218 stations for a region of this size is sufficient for a statistically valid representation of the region, and is similar to or greater than the number used in various precipitation studies in peer-reviewed scientific journals.<sup>82</sup> Also, using USHCN daily data rather than data from a broader set of weather stations offers offsetting values: The USHCN stations have been selected to be both representative and to have high-quality data; the station records are relatively complete; and the data have been reviewed and flagged where data questions exist (see below).

State-by-state results are reported, but with smaller numbers of stations per state, no claim of statistical validity is made with respect to them.

#### Time Period

The selection of 1961 through 2011 as the time period for the RMCO analysis was based on studies by Pavel Ya. Groisman and others from NCDC in their leading articles on trends in extreme precipitation,



which were published in 2004 and 2005.<sup>83</sup> The selection of this time period for the RMCO analysis is the first of several instances in which the RMCO analysis was patterned after the studies by Groisman and others, enabling a comparison of the results (see pages 18-19).

Beginning the analysis with 1961 made possible the same baseline period for some elements of the analysis as in the studies by Groisman and others (see below). Further, the analysis by Groisman and others showed there was no need to begin the RMCO analysis with any data from before 1961, as they determined that there was no significant trend to changes in very heavy precipitation prior to about 1970, either across the contiguous United States or in the Midwest.<sup>84</sup> As they wrote after carefully analyzing daily precipitation data since 1893, "it is probably a paradox that so much effort was made to collect, quality control, pre-process, and analyze data for the full 110 years, only to reveal that during the first 80 years no systematic changes occurred in very heavy precipitation frequency."<sup>85</sup>

Some elements of the RMCO analysis considered data through 2011. However, the USHCN daily precipitation data for 2011 will not be available until the summer of 2012, so it was not yet possible to use this dataset for 2011 data. Instead, preliminary daily precipitation data for the same USHCN weather stations were obtained from NCDC.<sup>86</sup> Other than the lack of data quality controls (see below), the preliminary 2011 data were analyzed the same way as the USHCN data for 1961-2010.

## Data Quality Controls

The USHCN provides data quality controls that are not available with any other weather stations in the United States. The daily precipitation data from the stations are reviewed by NCDC for various possible errors, and if the records for a day suggest the possibility of one, a quality flag is attached to that day's data denoting the type of potential error. In the RMCO analysis, for quality-control purposes daily data with any type of embedded quality flag were discarded from the analysis, and those days were treated as ones with missing data. This excluded data deemed suspect for having failed any of several NCDC quality checks, which include checks for accumulation totals, duplicates, gaps, internal consistency, streaks or frequent values, mega-consistency, naughty values, climatological outliers, lagged ranges, spatial consistency, temporal consistency, temperature too warm for snow, and values beyond bounds. Data with measurement or source quality flags were not discarded, as those flags do not relate to the accuracy of the data but instead to such matters as how values were calculated and the sources for them.

The preliminary data for 2011 have not been

subject to the USHCN quality reviews, and therefore no daily data were excluded and all reported daily data were used in the RMCO analysis.

## Analysis Methods

Missing data were addressed as follows. Annual rates were calculated by converting values for the days of a year with usable data to equivalent values for 365.25 days. If a station were missing data for more than half the days in a decade, all data for that specific decade was discarded, for both decadal and annual analyses. Requiring that a station have usable data for at least half the days in a decade was believed to be a reasonable minimum threshold to allow for extrapolation and comparison.

## Percentile Rankings

The RMCO analysis based on percentile rankings followed the approach used by Groisman and others in both 2004 and 2005. For each station, all usable days with precipitation in 1961 through 1990 were ranked by order of the amount of daily precipitation, the top 0.3% of those days were determined, and the threshold for that ranking was determined by the smallest amount of daily precipitation that qualified a day for that ranking. The same process was repeated for the top 1.0% of days with precipitation in 1961-1990. All days with precipitation from 1961 through 2010 were then evaluated to determine which met or exceeded those thresholds, and trends in those days were analyzed.

This analysis of heavy precipitation events on a percentile basis reflects local variations in rainfall amounts and measures trends based on local significance. By contrast, the analysis of days with absolute precipitation amounts above a certain threshold (such as three inches in a day) includes more or fewer days in a particular location, depending on the varying local frequency of days with precipitation above that absolute threshold. On the other hand, storms of at least three inches of precipitation in a single day are significant everywhere, regardless of their local frequency, and so there is independent merit to that analysis, too.

The regional and state-by-state average thresholds for the top 0.3% of all precipitation days are shown in Table App-2 on the next page.

## Areal Averaging

To avoid distorting results because of uneven geographic spacing of the analyzed stations, RMCO used areal averaging, in the same manner used by Thomas R. Karl and Richard W. Knight of NCDC in a 1998 article and by Groisman and others in their

Average Amounts of Precipitation in Top 0.3% of Daily Storms	
Midwest	2.95 inches
Illinois	3.21 inches
Indiana	2.93 inches
Iowa	3.34 inches
Michigan	2.29 inches
Minnesota	2.81 inches
Missouri	3.76 inches
Ohio	2.54 inches
Wisconsin	2.69 inches

Table App-2.

2004 and 2005 articles.<sup>87</sup> Where multiple stations are located in a single 1° by 1° latitude-longitude grid, the results from all stations in that grid were averaged together. Then the results from all grids (whether containing a single station or multiple stations) were averaged equally to produce regional and state results. Unlike Groisman and others, RMCO did not assign different weights to the results from different 1° grids to compensate for the relatively slight differences in their areas.

For the regional results reported here, all stations in a single grid were averaged together regardless of the state in which they are located. For separate state results, only the stations from a particular state were averaged together, excluding stations in the same grid but from a neighboring state. This was the case for 11 grids containing stations from two different states and one grid containing stations from three different states.

The numbers of grids for the region and by state are presented in Table App-3 above.

For the regional results, a total of 124 grids were utilized, with 67 of those grids containing one USHCN station, 32 containing two stations, 17 grids containing three stations, five grids containing four stations, two grids containing five stations, and one grid containing six stations.

## Baseline Period

For some parts of the RMCO analysis, for example in producing results shown in tables 1-12 and figures 1-11, precipitation data were compared to averages for those values over a baseline period of 1961-1990. This baseline period was originally chosen to match the baseline period used for the same purposes by

No. of 1-Degree Latitude/Longitude Grids	
Midwest	124
Illinois	18
Indiana	17
Iowa	15
Michigan	17
Minnesota	22
Missouri	18
Ohio	14
Wisconsin	15

Table App-3.

Groisman and others (2004 and 2005), enabling a comparison between the RMCO results by percentile rankings and those of Groisman and others (see pages 18-19).

## Trends and Statistical Analysis

The trends in annual values shown in tables 1 through 11 and in Figure 2 are over the period 1961 through 2011 (including preliminary data for 2011) and are trends per 51 years. The trends in annual values for storms by percentile rankings shown in tables 12 and 13 are over the period 1961 through 2010 (without preliminary data for 2011) and are trends per 50 years.

If the preliminary data for 2011 were not included, the trend in the annual values for frequency of three-inches-plus storms over the period 1961 through 2010 would be a 100% increase over 50 years. This trend is statistically significant according to a least-squares regression analysis and additional tests, as described below. For comparison, the trend in those annual values over the period 1961-2011 (including preliminary the data for 2011), which is a 103% increase over 51 years as shown in tables 2 and 3 and Figure 2, is equivalent to a 101% increase over 50 years.

All trends identified in this report as having statistical significance were found by a standard least-squares regression analysis to be significant with a 95% or higher level of confidence. In some cases, additional tests were made, as described next.

The trends in the region's annual frequency of three-inches-plus storms and top-0.3% storms, both for the period of 1961 through 2010, were also subjected to additional tests. (For the three-

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inches-plus storms, the inclusion of the preliminary data for 2011 would not affect the outcome of these additional tests.) A Kendall-tau rank correlation was employed and the two-sided p values were compared to the estimates produced by the least-squares regressions and found to be in agreement.<sup>88</sup> Additionally, Ann Hess, a statistics professor at Colorado State University, reviewed the least-squares regression analysis and also employed supplementary nonparametric methods (as did Groisman and others in 2004 and 2005).<sup>89</sup> Hess also checked the data for evidence of autocorrelation and found none. In part because the regression analysis indicated that the residuals were not normally distributed, Hess, using a free command-line program, "R," ran Theil-Sen regressions (a non-parametric alternative that does not require normality) and found that the Theil slopes were very close to the least-squares analyses. Kendall correlation tests (as employed by Groisman and others), performed by Hess using "R," also yielded evidence of statistically significant positive trends. The agreement of the three tests gives added confidence in the significance of the regional trends for both the 3-inches-plus and 0.3% events.

Throughout this report, where state or regional trends are not discussed as being statistically significant, no statistical significance can be assumed. In some cases involving state trends, the results for some but not all individual states would be statistically significant. In other cases, no significance tests were performed.

## **SOURCES AND METHODOLOGY FOR ANALYSIS OF 2008 STORMS**

To indicate the extent to which there is a relationship between the high frequency of extreme storms in calendar year 2008 revealed by the RMCO analysis and the flooding that occurred across the Midwest in June of that year (see pages 21-22), RMCO undertook an additional analysis.

RMCO used an NCDC map of all weather stations (not just USHCN stations) to determine which are in counties indicated by the Midwestern Regional Climate Center map constituting Figure 12 to have received 12 inches or more of precipitation in June 1-15, 2008.<sup>90</sup> The only stations excluded from the analysis were stations lacking data for 2008 or stations located close enough to a selected station that they were deemed to present danger of oversampling. In total, 27 weather stations from 24 counties were selected for the analysis. Eleven stations are in Wisconsin, eight in Iowa, seven in Indiana, and one in Illinois. Three counties in Wisconsin (Columbia, Jefferson, and Sauk) each contained two stations used in the analysis. Some counties within the 12-inch areas have no usable stations.

The analysis itself was a straightforward matter of analyzing the daily precipitation records for June 1-15, 2008.

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## NOTES

For general information on climate change and its overall impacts, readers are referred to a report by the U.S. government's Global Change Research Program, *Global Climate Impacts in the United States*, released in 2009, which is cited in many of the following notes, beginning with number 2. This national assessment is both comprehensive and, unlike most scientific publications, easily readable. For any reader interested in digging deeper, it also lists several hundred sources on particular points. Another particularly relevant U.S. government interagency report is *Weather and Climate Extremes in a Changing Climate: Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*, cited in note 5.

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3. USGCRP, *Climate Change Impacts* (see previous note), pp. 17-22, 32-36.
4. U.S. Geological Survey (USGS), *Large Floods in the United States: Where They Happen and Why*, J. E. O'Connor and J. E. Costa, authors, 2003, pp. 7-9, <http://pubs.usgs.gov/circ/2003/circ1245/pdf/circ1245.pdf>; National Climatic Data Center (NCDC), National Oceanic and Atmospheric Administration (NOAA), "Billion dollar U.S. weather/climate disasters, 1980-2011," N. Lott and others, authors, 2012, <http://www.ncdc.noaa.gov/img/reports/billion/billionz-2011.pdf>.
5. U.S. Climate Change Science Program (USCCSP), "Why weather and climate extremes matter," T. C. Peterson and others, authors, in USCCSP, *Weather and Climate Extremes in a Changing Climate: Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*, T. R. Karl and others, editors (Washington, DC: National Oceanic and Atmospheric Administration, 2008), p. 13, <http://downloads.climate-science.gov/sap/sap3-3/sap3-3-final-all.pdf>.
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7. NCDC, "Billion dollar disasters" (see note 4).
8. National Weather Service (NWS), NOAA, "National Hazard Statistics," <http://www.nws.noaa.gov/os/haz-stats.shtml>; USCCSP, "Why extremes matter" (see note 5), p. 16.
9. USGCRP, *Climate Change Impacts* (see note 2), p. 32.
10. To be published soon is an article that considers data through 2010. P. Ya. Groisman, R. W. Knight, and T. R. Karl, "Changes in intense precipitation over the central U.S.," *Journal of Hydrometeorology* (forthcoming).
11. For example, National Weather Service (NWS) Weather Forecast Office, St. Louis, MO, "Northeast Missouri Flash Flood Event: July 20th, 2010," [http://www.crh.noaa.gov/lx/?n=07\\_20\\_2010](http://www.crh.noaa.gov/lx/?n=07_20_2010).
12. National Hurricane Center, NWS, "Tropical Cyclone Climatology," <http://www.nhc.noaa.gov/climo/#returns>.
13. USGCRP, *Climate Change Impacts* (see note 2), pp. 32, 44.
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18. USCCSP, "Observed changes in weather and climate extremes," K. E. Kunkel and others, authors, in USCCSP, *Weather and Climate Extremes* (see note 5), p. 49.
19. USGCRP, *Climate Change Impacts* (see note 2), p. 32.
20. USCCSP, "Why extremes matter" (see note 5), p. 18.
21. USGS, *Large Floods in the United States* (see note 4), pp. 7-9.
22. The source for all facts in this paragraph is NCDC, "Billion dollar disasters" (see note 4). Costs in the text are in 2011 dollars.
23. NWS, "United States Flood Loss Report - Water Year 2010," <http://www.nws.noaa.gov/hic/summaries/WY2010.pdf>.
24. NCDC, "Billion dollar disasters" (see note 4).
25. The sources for all facts in this paragraph are



- results obtained from searches by year and state for disaster type: flooding, at Federal Emergency Management Agency (FEMA), "2012 federal disaster declarations," <http://www.fema.gov/news/disasters.fema>.
26. NCDC, "2008 midwestern U.S. floods," <http://www.ncdc.noaa.gov/special-reports/2008-floods.html>.
  27. NCDC, "2008 midwestern U.S. floods" (see previous note).
  28. NCDC, "2008 midwestern U.S. floods" (see note 26).
  29. USGS, *Flooding in the United States Midwest, 2008*, R. R. Holmes, Jr., T. A. Koenig, and K. A. Karstensen, authors (Reston, VA: USGS, 2010), figure 12, pp. 16-17, <http://pubs.usgs.gov/pp/1775/>.
  30. Image by Midwestern Regional Climate Center, available in NCDC, "2008 midwestern U.S. floods" (see note 26).
  31. USCCSP, *Weather and Climate Extremes* (see note 5), p. 3.
  32. S. E. Morlock and others, "Flood of June 7-9, 2008, in central and southern Indiana," USGS, 2008, available at <http://pubs.usgs.gov/of/2008/1322/>.
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  34. Advanced Hydrologic Prediction Service, NWS, "East Fork White River at Columbus," <http://water.weather.gov/ahps2/hydrograph.php?wfo=ind&gage=baki3>.
  35. NWS, "East Fork White River at Columbus" (see previous note).
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  37. Kanehl, "Columbus flood of the century" (see previous note).
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  39. USCCSP, "Why extremes matter" (see note 5), pp. 26-27.
  40. F. C. Curriero and others, "The association between extreme precipitations and waterborne disease outbreaks in the United States, 1948-1994," *American Journal of Public Health*, vol. 91, no. 8 (2001), pp. 1194-1199, <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1446745/>.
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  42. Corso and others, "Cost of illness" (see previous note), pp. 426-431.
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  44. Natural Resources Defense Council (NRDC), *Rooftops to Rivers: Green Strategies for Controlling Stormwater and Combined Sewer Overflows*, C. Kloss and C. Calarusse, authors (New York, NY: NRDC, 2006), p. 3, <http://www.nrdc.org/water/pollution/rooftops/rooftops.pdf>.
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  46. For example, USGCRP, *Climate Change Impacts* (see note 2), pp. 17-22, 24, 32-36; USCCP, *Weather and Climate Extremes* (see note 5).
  47. USGCRP, *Climate Change Impacts* (see note 2), p. 9.
  48. Intergovernmental Panel on Climate Change (IPCC), "Summary for policymakers," R. Alley and others, authors, in IPCC, *Climate Change 2007: The Physical Science Basis*, S. Solomon and others, editors (Cambridge, U.K.: Cambridge University Press, 2007), pp. 3, 8, <http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf>.
  49. USGCRP, *Climate Change Impacts* (see note 2), pp. 16, 19-20; IPCC, "Technical summary," S. Solomon and others, authors, in IPCC, *The Physical Science Basis* (see previous note), p. 60.
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  52. USCCSP, "Causes of observed changes in extremes and projections of future changes," T. J. Gutkowski and others, authors, in *Weather and Climate Extremes* (see note 5), pp. 89, 98.
  53. USCCSP, "Causes and projections" (see previous note), pp. 89-90, 98; USGCRP, *Climate Change Impacts* (see note 2), pp. 20-22.
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59. K. E. Trenberth, "Framing the way to relate climate extremes to climate change," *Climatic Change*, published online Mar. 21, 2012, <http://www.springer-link.com/content/0008xl84w0743102/fulltext.pdf>.

60. IPCC, "Global climate projections," G. A. Meehl and T. F. Stocker, lead authors, in IPCC, *The Physical Science Basis* (see note 48), pp. 782, 784; IPCC, "Summary for Policymakers" (see note 48), p. 8; USGCRP, *Climate Change Impacts* (see note 2), pp. 32, 44; USCCSP, "Causes and projections" (see note 52), figure 3.1, p. 88, pp. 100, 102–104.

61. IPCC, "Global climate projections" (see previous note), p. 785, figure 10.18; USGCRP, *Climate Change Impacts* (see note 2), pp. 25, 32; USCCSP, "Causes and projections" (see note 52), figure 3.1, p. 88.

62. USGCRP, *Climate Change Impacts* (see note 2), p. 25.

63. USGCRP, *Climate Change Impacts* (see note 2), p. 25. The emissions scenario referred to in the figure as the "higher emissions scenario" is scenario A2, and that referred to as the "lower emissions scenario" is scenario B1, from among the scenarios developed for IPCC reports published in 2007; see USGCRP, *Climate Change Impacts* (see note 2), pp. 22–24. Since in recent years emissions have been higher than assumed in the A2 scenario, it now is often styled a "medium-high" scenario; see, for example, S. Moser and others, "The future is now: An update on climate change science impacts and response options for California," California Climate Change Center, 2009, p. 40, <http://www.energy.ca.gov/2008publications/CEC-500-2008-071/CEC-500-2008-071.PDF>.

64. Figure reproduced from USGCRP, *Climate Change Impacts* (see note 2), p. 32. For the identity of the emissions scenarios referred to in the figure, see note 60. See also USCCSP, "Causes and projections" (see note 52), p. 102; USGCRP, *Climate Change Impacts* (see note 2), p. 44.

65. USGCRP, *Climate Change Impacts* (see note 2), p. 32.

66. USGCRP, *Climate Change Impacts* (see note 2), p. 44.

67. USCCSP, "Causes and projections" (see note 52), p. 100, figure 3.5b.

68. WICCI, *Wisconsin's Changing Climate* (see note 17), p. 32.

69. Based on figures in WICCI, *Wisconsin's Changing Climate* (see note 17), p. 32. See also WICCI, "Climate working group report," 2011, pp. 14–15, and figure 13, p. 45, available at <http://www.wicci.wisc.edu/publications.php>. The columns in the table for "lower future emissions" refer to emissions scenario B1 and for "medium-high future emissions" refer to emissions scenario A2. WICCI refers to scenario A2 as "higher"; see note 63 for an explanation of

these scenarios and how they are characterized. The models used in WICCI's analysis are from the World Climate Research Program's Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset, available at [http://gdo-dcp.ucllnl.org/downscaled\\_cmip3\\_projections/](http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/); however, the WICCI report does not indicate which model runs from that dataset were used.

70. WICCI, "Climate working group report" (see previous note), p. 15.

71. USGCRP, *Climate Change Impacts* (see note 2), p. 44.

72. M.R. Raupach and others, "Global and regional drivers of accelerating CO<sub>2</sub> emissions," *Proceedings of the National Academy of Sciences*, vol. 104 (2007), pp. 10288–10293. In the nine years from 2000 to 2009, emissions from fossil-fuel burning grew by 28%, compared to 11% over the previous nine years, the time during which the current emissions scenarios were developed (U.S. Energy Information Administration (USEIA), "Total carbon dioxide emissions from the consumption of energy," spreadsheet available at USEIA, "International energy statistics," <http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=90&pid=44&aid=8>).

73. R. H. Moss and others, "The next generation of scenarios for climate change research and assessment," *Nature*, vol. 463 (2010), pp. 747–756; D. P. van Vuuren, "The representative concentration pathways: An overview," *Climatic Change*, vol. 109 (2011), pp. 5–31; International Institute for Applied System Analysis, "RCP database (version 2)," <http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=welcome#citation>.

74. USGCRP, *Climate Change Impacts* (see note 2), p. 24.

75. Figure obtained from IPCC, "Figures and tables," figure 3-1, [http://www.ipcc.ch/publications\\_and\\_data/publications\\_and\\_data\\_figures\\_and\\_tables.shtml#.T5h36tnsoxw](http://www.ipcc.ch/publications_and_data/publications_and_data_figures_and_tables.shtml#.T5h36tnsoxw).

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77. Philadelphia Water Department, *Green City, Clean Water: The City of Philadelphia's Program for Combined Sewer Overflow Control* (2011), [http://www.phillywatersheds.org/doc/GCCW\\_AmendedJune2011\\_LOWRES-web.pdf](http://www.phillywatersheds.org/doc/GCCW_AmendedJune2011_LOWRES-web.pdf).

78. USGCRP, *Climate Change Impacts* (see note 2), p. 12.

79. M. J. Menne, C. N. Williams, Jr., and R. S. Vose, "USHCN: Long-term daily and monthly climate records from stations across the contiguous United States," <http://cdiac.ornl.gov/epubs/ndp/ushcn/background.html>.

80. T. R. Karl and R. W. Knight, "Secular trends of

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precipitation amount, frequency, and intensity in the United States," *Bulletin of the American Meteorological Society*, vol. 79 (1998), pp. 231-241; A. T. DeGaetano, "Time-Dependent Changes in Extreme-Precipitation Return-Period Amount in the Continental United States," *International Journal of Climatology*, vol. 48 (2009), pp. 2086-2099, [http://www.hydrology.bee.cornell.edu/BEE3710Handouts/Degaetano-APPMETCLI09\\_extremeprecip.pdf](http://www.hydrology.bee.cornell.edu/BEE3710Handouts/Degaetano-APPMETCLI09_extremeprecip.pdf).

81. USCCSP, "Observed changes in weather and climate extremes," K. E. Kunkel and others, authors, in USCCSP, *Weather and Climate Extremes* (see note 5), p. 46.

82. For example, G. Villarini and others, "On the frequency of heavy rainfall for the Midwest of the United States," *Journal of Hydrology*, vol. 400 (2011), pp. 103-120 (using 221 weather stations to analyze trends in nine states); N. M. Hitchens and others, "Characterizing subdiurnal extreme precipitation in the midwestern United States," *Journal of Hydro-meteorology*, vol. 11 (2010), pp. 211-218 (using 48 stations to analyze trends in the same eight midwestern states analyzed in this report), <http://journals.ametsoc.org/doi/abs/10.1175/2009JHM1129.1>.

83. P. Ya. Groisman and others, "Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations," *Journal of Hydrometeorology*, vol. 5 (2004), pp. 64-85; P. Ya. Groisman and others, "Trends in intense precipitation in the climate record," *Journal of Climate*, vol. 18 (2005), pp. 1326-1350, p. 1336.

84. Groisman and others, "Contemporary changes of the hydrological cycle" (see previous note), pp. 64-85, p. 83.

85. Groisman and others, "Trends in intense precipitation" (see note 84), p. 1336.

86. NCDC, "Daily Observational Data," <http://gis.ncdc.noaa.gov/map/cdo/?thm=themeDaily>.

87. For the article by Karl and Knight, see note 80.

88. The free statistics software website, [http://www.wessa.net/rwasp\\_kendall.wasp#top](http://www.wessa.net/rwasp_kendall.wasp#top), was used to produce the Kendall tau rank correlation analysis.

89. A. Hess, assistant professor of statistics, Colorado State University, personal communication (emails to D. Findlay), Nov. 1, 2011, and Jan. 26, 2012.

90. NCDC, "Daily Observational Data," see note 86.